PB81-213365

Effect of Flue Gas Cleaning Sludges on Selected Liner Materials

(U.S.) Army Engineer Waterways Experiment Station, Vicksburg, MS

Prepared for

Municipal Environmental Research Lab.
Cincinnati, OH

Jun 81

U.S. Department of Commerce
National Technical Information Service
NTIS.

EPA-600/2-81-098
June 1981

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by

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Interagency Agreement No. EPA-IAG-D5/6-0785

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CINCINNATI, OHIO 45268

PRODUCT OF:
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA-600/2-81-098	ORD Report	PB81 213365

4. TITLE AND SUBTITLE	5. REPORT DATE
Effects of Flue Gas Cleaning Sludge on Selected Liner Materials	June 1981
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Clarence R. Styron III, Zelma D. Fry, Jr. Gordon L. Carr	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
U.S. Army Engineer Waterways Experiment Station Vicksburg, Mississippi 39180	11. CONTRACT/GRANT NO. IAG-D5/6-0785

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Municipal Environmental Research Laboratory - Cin.,OH Solid and Hazardous Waste Research Division U.S. Environmental Protection Agency Cincinnati, Ohio 45268	Final 14. SPONSORING AGENCY CODE EPA/600/14

15. SUPPLEMENTARY NOTES

Project Officer - Robert E. Landreth 513/684-7871

16. ABSTRACT

This project examines the effects of two flue gas desulfurization (FGD) sludges on 18 liner materials used to contain them. Seventy-two special test cells were constructed 1 ft. in diameter by 2 ft. high. Devices were installed to collect the leachate from each test cell for determination of the quantity of leakage and the leakage rate (permeability), and to provide storage for subsequent chemical analyses. Ten admix liner materials were mixed with a clayey silt and compacted in the bottom 6 in. of the test cells. Six spray-on and two prefabricated membrane liners were placed over 6 in. of compacted silty sand. Four gallons of sludge was then added to each test cell along with enough tap water to bring the liquid to within 4 in. of the top. Each test cell was covered and pressurized to simulate a disposal area approximately 30 ft. deep.

Physical and chemical tests were conducted on the liners before exposure to the FGD sludges, and after 12 and 24 months of exposure.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Wastes Sludge Linings Plastic Decomposition Reactions Flue Gases	Flue Gas Cleaning Chemical Stabilization Sludge Liner	13 B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
Release to Public	Unclassified	
	20. SECURITY CLASS *(This page)*	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

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FOREWORD

The U. S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution; it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and solid and hazardous waste pollutant discharges from municipal and community sources to preserve and treat public drinking water supplies and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and provides a most vital communication link between the research and the user community.

This final report presents the results of physical and chemical tests and analyses of materials tested as liners for industrial waste disposal sites. The tests followed 24 months of inundation in actual wastes to simulated depths of 30 ft. Also presented are construction techniques and cost.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This project examines the effects of two flue gas desulfurization (FGD) sludges on 18 liner materials used to contain them. Seventy-two special test cells were constructed 1 ft in diameter by 2 ft high. Devices were installed to collect the leachate from each test cell for determination of the quantity of leakage and the leakage rate (permeability), and to provide storage for subsequent chemical analyses. Ten admix liner materials were mixed with a clayey silt and compacted in the bottom 6 in. of the test cells. Six spray-on and two prefabricated membrane liners were placed over 6 in. of compacted silty sand. Four gallons of sludge was then added to each test cell along with enough tap water to bring the liquid to within 4 in. of the top. Each test cell was covered and pressurized to simulate a disposal area approximately 30 ft deep.

Physical tests of the 18 liner materials were conducted before exposure to the FGD sludges, and after 12 and 24 months of exposure. Chemical tests for determination of heavy metals were conducted on the two sludges as received and on the sludge liquor that passed through the lined test cells after 12 and 24 months.

This final report follows the 1979 interim report, Flue Gas Cleaning Sludge-Leachate Liner Compatibility Investigation (EPA-600/2-79-136).

This report was submitted in fulfillment of Interagency Agreement EPA-IAG-D5/6-0785 between the U. S. Environmental Protection Agency and the U. S. Army Engineer Waterways Experiment Station. This report covers the test period April 15, 1975, through September 30, 1978, and work was completed as of August 1980.

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METRIC CONVERSION FACTORS

Multiply	By	To Obtain
cubic feet	0.028317	meters
Fahrenheit degrees*	5/9	Celsius degrees or Kelvin*
feet	0.3048	meters
gallons (U. S. liquid)	3.785412	cubic decimeters
gallons per square yard	4.5273	cubic decimeters per square meter
inches	25.4	millimeters
mils	0.0254	millimeters
ounces (U. S. fluid)	29.57353	cubic centimeters
ounces (mass) per square yard	33.90375	grams per square meter
poises (absolute viscosity)	0.1000	pascal seconds
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	6894.757	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic meter
pounds (mass) per gallon (U. S. liquid)	119.826	kilograms per cubic meter
tons (2000 lb, mass) per acre)	0.22417	kilograms per square meter

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

ABBREVIATIONS AND SYMBOLS

A	-- area
As	-- arsenic
ASTM	-- American Society for Testing and Materials
avg	-- averages
B	-- boron
Be	-- beryllium
Cd	-- cadmium
^{o}C	-- degrees Celsius
cm/sec	-- centimeters per second
Cn	-- cyanide
Cl	-- chloride
Cr	-- chromium
Cu	-- copper
EPA	-- U. S. Environmental Protection Agency
^{o}F	-- degrees Fahrenheit
ft_3	-- foot (feet)
ft^3	-- cubic feet
FGD	-- flue gas desulfurization
g	-- gram(s)
gal	-- gallon(s)
G_s	-- specific gravity
Hg	-- mercury
hp	-- horsepower
i	-- average hydraulic gradient during t
in.	-- inch
lb/ft^3	-- pounds per cubic foot
Mg	-- magnesium
mg/l	-- milligrams per liter
Mn	-- manganese
Ni	-- nickel
NO_2, N	-- nitrogen nitrite
NO_3, N	-- nitrogen nitrate
OD	-- outside diameter
oz	-- ounces
oz/yd^2	-- ounces per sq yd
Pb	-- lead
ppm	-- parts per million
psi	-- pounds per square inch
psig	-- pounds per square inch gage
PVC	-- polyvinyl chloride
Q	-- quantity of leachate collected
Se	-- selenium
SLT	-- standard laboratory techniques
SO_3	-- sulfite
SO_4	-- sulfate
t	-- time period during collection of leakage
TCA	-- test cell apparatus
UC	-- unconfined compression
USCS	-- unified soil classification system
V	-- vanadium
WES	-- Waterways Experiment Station
Zn	-- zinc
ΔH	-- change in height

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Dr. Larry W. Jones and Dr. Phillip G. Malone, U. S. Army Engineer Waterways Experiment Station, for providing analysis and discussion of the chemical tests.

Special thanks are also directed to Mr. Gerald T. Easley, Geotechnical Laboratory, U. S. Army Engineer Waterways Experiment Station, who designed the test cell and ancillary equipment and supervised all procurement and fabrication.

The authors also wish to thank Mr. Robert E. Landreth and Mr. Norbert B. Schomaker for their support and guidance during this phase of the project.

SECTION 1

INTRODUCTION

BACKGROUND AND OBJECTIVES

The industrialization of this country has had a very significant impact on the environment. Many industries produce wastes that may be highly toxic to the environment if proper controls are not used. As the volumes of these wastes increase, disposal problems are multiplied, both with regard to availability of land space and the economics dictating development of new disposal technology. The U. S. Environmental Protection Agency (EPA) Report to Congress on Hazardous Waste Disposal in 1973 (1) concluded that the then existing management of hazardous wastes was generally inadequate and that the public health and welfare were threatened by the uncontrolled disposal of such waste materials into the environment.

The potential impact of inadequate hazardous waste management is the contamination of ground and surface waters, which can occur from improperly located, designed, or operated disposal sites. The potential exists because within a disposal site, various physical, chemical, and biological processes occur from water or fluid percolating through the wastes and producing a leachate with the potential for contaminating the groundwater. Controlling the leachate by lining the disposal area with an impervious material could be a solution to the problem, and it would allow the utilization of more sites for disposal areas. The use of liners for such purposes is not a new concept, but knowledge is lacking on the compatibility of liner materials subjected to certain toxic wastes and particularly on the life expectancy of such liners. Considerably more information is needed to supply guidance and possible future regulations for use of liners in waste disposal areas.

This study was undertaken with the following objectives:

a. To determine the compatibility of liner materials with flue gas desulfurization (FGD) sludges and associated liquors and leachates;

b. To estimate the length of life for the liners; and

c. To assess the economics involved with the purchase and placement (including construction) of various liner materials.

To realize these study objectives, the liner materials were subjected

to a simulated 30-ft* head (depth) of sludge, as would be expected in disposal ponds.

This report describes the test from its inception through the 24-month exposure period and/or the end of the test in the following order of events:

a. The methodology and research approach.

b. The construction of the test cells and ancillary equipment.

c. The selection of the various liners and wastes (sludges).

d. The preparation of the liners and sludges and installation in the test cells.

e. Determination of physical properties of the liners and chemical analyses of the sludges and leachates for zero time (unexposed) and for 12- and 24-month exposure periods.

f. Estimates and/or projected service life of the liners.

g. Economic assessments of the liners.

SUMMARY

Seventy-two special test cells were constructed to study the compatibility of 18 liner materials with two selected FGD sludges. Devices were installed to collect the leachate from each test cell to determine the quantity of leakage and the leakage rate (permeability) and to provide storage for subsequent chemical analyses. The test cells were pressurized to simulate a disposal area approximately 30 ft deep. Physical tests of the 18 liner materials were conducted before exposure to the FGD sludge and after 12 and 24 months of exposure.

Five of the admix liner materials (Portland cement, lime, cement plus lime, C400, and CST) were tested in unconfined compression (UC) following 12- and 24-month exposures to both sludges. The UC values after 12 months were approximately double the zero time (control) values, and they were generally slightly higher after 24 months. Both the UC values for TACSS 020 and TACSS 025 decreased approximately 13 percent after 12 months, and the TACSS 020 decreased another 11 percent during the second 12 months. No UC data were obtained on the TACSS 025 for 24 months, as the sample dissociated. Guartec UF and M179 proved incompatible with either sludge type, and the testing of these two products was discontinued after 12 months. The asphaltic concrete liner exhibited extensive cracks after 12 months, and the cracking continued to increase during the second 12 months. The penetration and viscosity of the asphalt increased approximately 10 percent at 12 months. At 24 months, the penetration remained constant, whereas the viscosity decreased more than

* A table for converting U. S. customary units of measure to metric (SI) units is given on page x.

16 percent. The breaking strength of the spray-on and membrane liners decreased without exception after 12 months, and all of the breaking strength values increased approximately 10 percent after 24 months, except those for DCA-1295, which continued to decrease during the 24-month period.

The percent of elongation values for the Total Liner material increased approximately 400 percent the first year. The elongation values for T16, Dynatech, and Uniroyal generally remained constant throughout the test period (2 years). At 24 months, the Aerospray 70 reversed its pattern from 12 months by increasing, and the DCA-1295 continued to decrease.

To determine the concentrations of 20 heavy metals, chemical tests were conducted on the two FGD sludges as received and on the FGD sludge liquor that passed through the lined test cells after 12 and 24 months, and the data were tabulated. Increasing concentrations of some of the heavy metals indicated liner breakdown and/or penetration by the sludge material in the case of Guartec UF, M179, and two TACSS materials after 12 months. Tests on the former two liners were discontinued at the end of 12 months. The chloride concentration of the liquor collected beneath each test cell is presented separately as an indication of how the sludge liquor moves through the liner/soil combination. For example, these data indicate that the AC40 and Sucoat both had liquor moving through the entire cross section of the liner. Should liquor continue to pass through these or similar liner materials in a real situation, the discharge would be expected to approach the composition of the sludge liquor.

APPROACH AND RESEARCH PLAN

To meet the objectives of this study, the overall experimental approach was to expose specimens of a variety of potential liner materials to selected FGD sludge wastes over a period of time under conditions that simulated disposal areas and to determine changes in the physical properties of the liner material with exposure time.

Because of the type of material to be disposed of, the volume, and related economic considerations, the selection of potential liner candidates was initially limited to those that were relatively inexpensive. However, ease of placement and construction costs were also considered as possible offsets to high material costs. Primary consideration was placed on the use of admixed or stabilized in situ liner material; next in importance was the use of spray-on materials; and finally, limited use was made of prefabricated membrane-type liner materials. The membrane- or polymeric-type liners are being tested extensively in other EPA-supported projects (2-4). From the above categories, the requirement was to select a total of 18 liner types for inclusion in the study. Two FGD sludges were selected.

Specifically, the plan was:

a. To select liner materials that have the potential for being used as liners for FGD sludge disposal areas.

b. To design and construct test cells simulating the conditions under which liner materials would exist in a disposal area. (The test

cells were to be capable of simulating a depth of sludge of at least 30 ft that could be applied in increments over a period of time.)

c. To select the FGD sludge that would be representative of those expected to be encountered in disposal areas.

d. To characterize the FGD sludge so that behavior of selected liners could be predicted for required exposure periods.

e. To expose the liner materials for 12- and 24-month periods.

f. To subject the liner materials to physical tests to determine the characteristics of the liners at each of the three data points (i.e. zero, 12, and 24 months) to provide information regarding behavior over a period of time.

g. To collect and measure the quality of the permeate, if any, of the sludge leachate through the liners.

h. To analyze the permeate of the 12- and 24-month periods for the 20 parameters used to indicate water quality. (The analyses will be conducted at a sensitivity equal to that obtainable by flame AA spectrophotometry.)

i. To develop cost data for the liners.

SECTION 2

CONCLUSIONS

Experimental studies on liner/sludge compatibility indicated that Guartec UF and M179 materials are unsatisfactory for landfill liners. Liners that permitted zero permeability (impervious) indicated that they were suitable for landfill liners for a period of 2 years. Continuous studies are needed to confirm their use for longer periods and/or to project their useful life.

The interface bond between the silicone sealant and the wide variety of liners is incompatible in some cases and contributes to inconsistent permeability data. The wide range of liners studied makes it almost impossible to find one sealant that will adhere adequately to each liner.

The serviceability or durability data for asphalts obtained by penetration and viscosity may be valid for a variety or family of asphalts, but these data are not useful to compare with grab test and UC data obtained on the other liner materials.

The C400 and CST liners data were very similar to that of the Portland cement. The strengths of these materials tended to increase significantly during the first year and generally remained constant during the second year.

After 12 months, the strength of the liners tested by the grab test tended to level off or increase, except the DCA-1295, which continued to lose strength.

The percent of elongation values for the Total Liner material increased approximately 400 percent the first year and remained constant the second year. The values for T16, Dynatech, and Uniroyal generally remained constant throughout the 2-year test period.

SECTION 3

RECOMMENDATIONS

Similar tests should be continued utilizing an improved test cell that will eliminate possible interference with the test data collected. The test cell used should eliminate the need for a silicone sealant or the techniques using the adhesives should be improved to produce comparable test data. The need for an adhesive would be eliminated for the spray-on and prefabricated liners by slicing a cell and then joining the two slices positively, or by using a cell similar to the test device for checking pinholes. The improved test cell should provide consistent, reliable, and comparable data.

Studies and tests should be initiated to develop data that can predict and/or project the expected life of a liner material exposed to various sludges and chemicals. Also, accelerated weathering tests on the liners should be developed, and a series of tests should be undertaken to compress the time required in similar tests.

Tests should be developed that would make a more accurate comparison of data from admix, spray-on, prefabricated, and asphaltic-type liner materials.

SECTION 4

METHODS AND MATERIALS

DESIGN AND CONSTRUCTION OF TEST CELLS AND ANCILLARY EQUIPMENT

Design considerations for the test cells and the special equipment and materials required are discussed in this section.

General Design Considerations

Several factors were considered for the design of the test cells. These factors included the methods for constructing or installing liners for field installations (5), the size or amount of a specimen required for physical tests at the termination of exposure periods, a cell volume sufficient to contain the liner and sludge, and a means of simulating a 30-ft depth of sludge.

The admix liners constitute the largest number of liners selected for this study. Admix materials are usually chemicals added to a road base or runway base soil in small quantities (normally 4 to 10 percent of the dry soil weight) to improve some particular physical qualities of the soil. They can be mixed at the site by covering the area to be treated with the chosen amount of additive and then mixing it with the underlying soil using a mixing device such as the Pettibone mixer (Figure 1). This machine, along with others such as the road grader and dozer, is used to process and move large quantities of soil economically. Because of the size of these machines and the normally undulating terrain, 6 in. is judged to be the minimum practicable depth to stabilize, even when the admix material is mixed with the soil at a batch plant and transported to the site for spreading and compacting.

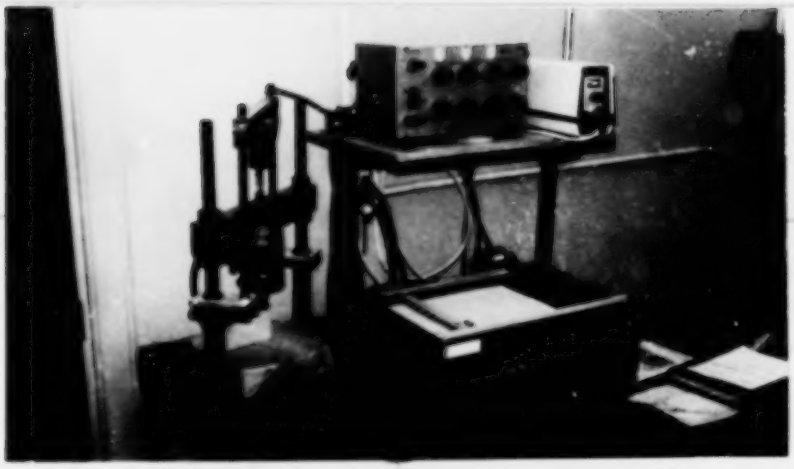
Spray-on materials should be applied to level areas, or at least to areas free of vertical or nearly vertical surfaces (i.e., wheel ruts). Usually some work is required to ready a site before a spray-on material can be applied. Ideally, all vegetation, sticks, roots, and large rocks should be removed, and the area rolled and prewet before the spray-on is applied.

Both spray-on materials and membranes require some protection against differential soil settlement. Membranes are simply left wrinkled, with the idea being that enough slack will be available to keep any resulting differential soil settlement from rupturing the membrane. Differential soil movement can easily rupture spray-on materials, rendering the liner ineffective. Therefore, the soil must be relatively smooth, and the compaction effort must be uniform and closely controlled.

Figure 1. Pettibone mixer.

The best method for limiting differential soil movement is through compaction of the soil before placement of the spray-on material. From a practical standpoint, the minimum depth of compaction should be 6 in. Thus it was decided that the liners would be tested with 6 in. of compacted soil in each case. With the admix materials, the liner is mixed with the compacted soil to a depth of 6 in., whereas the spray-on and membrane liners cover 6 in. of compacted soil. Any leachate would be forced to permeate a liner material and 6 in. of compacted soil, thus assuring comparable conditions.

The size of each liner specimen was determined by the number and type of tests following the exposure period. Nondestructive-type tests could only be used to detect swelling, shrinking, or obvious deterioration. Destructive-type tests were required to determine changes in liner strength and elasticity. The UC test was selected as a standard for the admix materials, and the grab test was chosen for the spray-on and membrane liners. Duplicate specimens were used for each test and the results averaged, whereas penetration and viscosity were used for the asphalt liner materials. Duplicate specimens were also valuable for determining unusual test results and for determining when additional testing was necessary. The UC test (American Society for Testing and Materials (ASTM) Method D 2166-66) (6) requires specimens approximately 1.2 in. in diameter by 2.8 in. high, whereas the grab test (ASTM D 1682-64) (7) requires 6- by 4-in. specimens. The UC and grab test equipment is pictured in Figure 2. The asphalt penetration and viscosity tests were conducted by ASTM D 5 and D 2170 and D 2171, respectively.



a. UC machine and recorder.

b. Instron machine with grab test attachments.

Figure 2. UC and grab test equipment.

Pressurization was considered to be the most feasible approach to simulate a 30-ft depth of sludge. This procedure necessitated an enclosed system and a pressure source sufficient to supply 20 psi to each test cell. The use of pressure permitted the use of minimum amounts of other materials, including sludge. Four gallons of sludge was arbitrarily chosen as a sufficient amount for a 2-year exposure period.

Test Cell Construction

Polyvinyl chloride (PVC) was selected for construction of the test cells. PVC was considered to be an inert material that would not react chemically with the FGD sludge. Schedule 80 PVC pipe, ID 11-13/16 in. with a pressure tolerance of 130 psi, was selected for the pressure cells. The base, also PVC, was 2-1/2 in. thick and 15 in. square. The base was tapped at the center to accommodate the drain port, and a special recess was provided to house a 6-in.-diameter and a 1/4-in.-thick porous plastic disc. The PVC top was 15 in. in diameter and 3/8 in. thick, with a tap provided for pressure attachments. The top, flanges, and base were drilled to accommodate 3/8-in. bolts for connection purposes. A schematic drawing of the test cell with ancillary equipment is shown in Figure 3. An exploded view of the cell is shown in Figure 4, and an assembled cell is shown in Figure 5. An additional top plate of 1/4-in. aluminum was required to prevent buckling of the PVC top as pressure was increased in the cell.

Seventy-two cells were fabricated. The initial step in assembly was attachment of the baseplate to the cylindrical body. A silicone sealant was applied at the interface of the flange and baseplate, and the bolts were secured. The same procedure was used for the coverplate after installation of the liner and sludge (the placement of liners and sludge is discussed in Section 7). After assembly, the cells were placed in a holding room on racks previously constructed, as shown in Figure 6. The holding room was capable of maintaining a constant temperature of 68°F and 40 percent humidity. In this manner, 18 liner types were exposed to two sludge types for 12 months. Thirty-six cells were required. A second set of 36 test cells was assembled at the same time for 24 months of exposure.

Ancillary Equipment

The ancillary components consisted of a pressure system for pressurization of the test cells and a system to collect the leachate.

For the pressure system, a 2-hp compressor was used to supply compressed air through a piping system to a series of manifolds from which plastic tubing was used to connect to each individual cell (Figures 3 and 6). Regulators and check valves were used between the compressor and manifolds for control of the desired pressure and as a safety measure against rapid depressurization should a failure occur. A second compressor was installed for use as required.

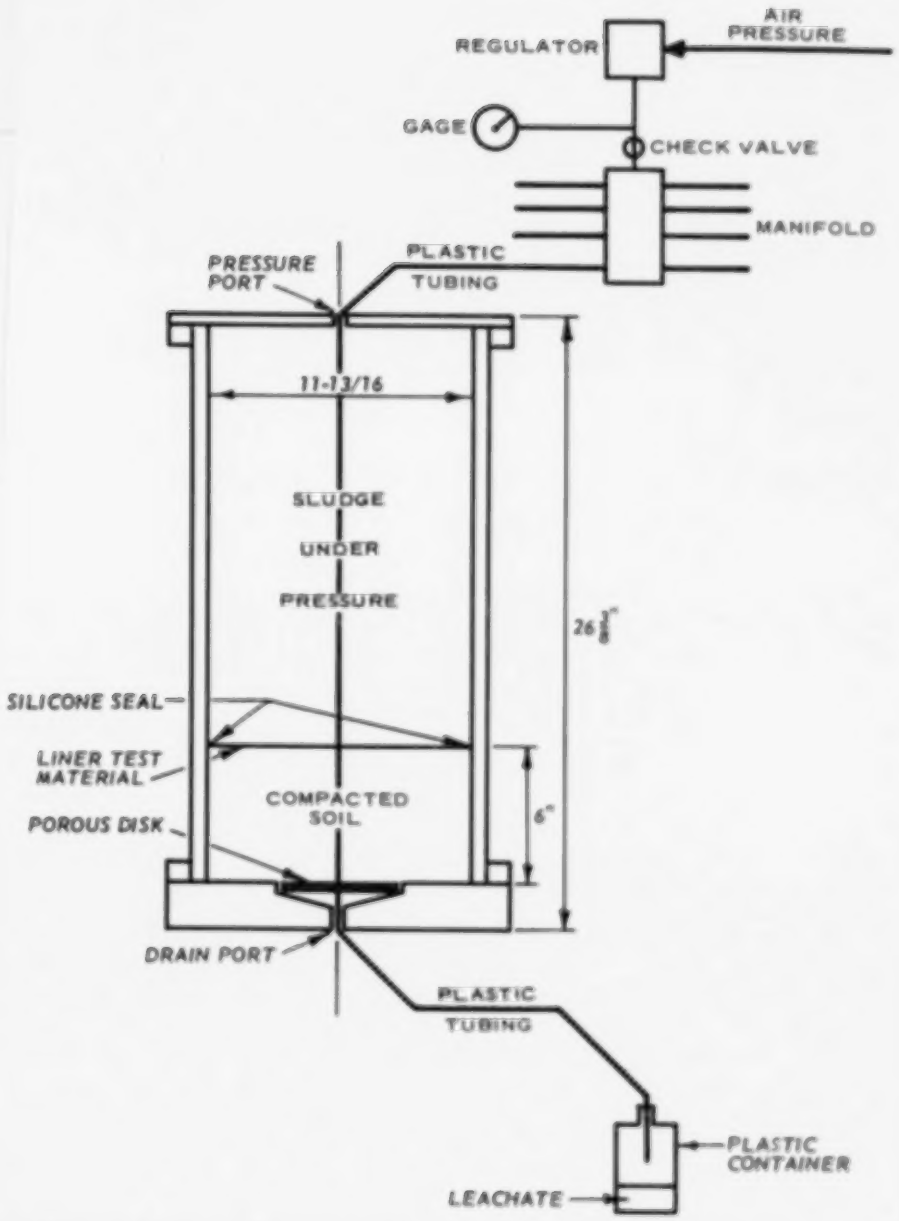


Figure 3. Schematic of a test cell section with a spray-on or membrane liner depicted and ancillary equipment.

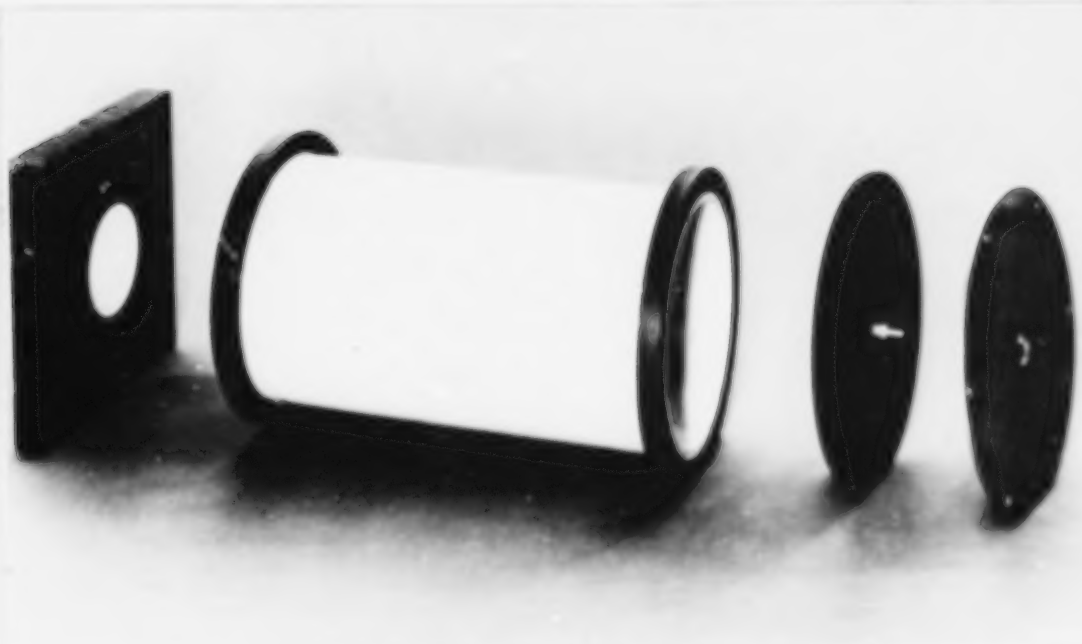


Figure 4. Exploded view of a typical test cell.

Figure 5. Assembled test cell.

Figure 6. Assembled test cells on racks in holding area.

FGD SLUDGE SELECTION AND CHARACTERISTICS

Selection

The two FGD sludges used in this study were selected from a group included in an EPA-supported research project at the WES (8). The group included FGD sludge from five different power plant locations from which samples had been previously obtained and characterized by chemical analyses (Table 1). Based on the available information, EPA recommended two sludges--one from an eastern coal lime-scrubbed process (Sludge A) and one from an eastern coal limestone-scrubbed process (Sludge B). The sludges were obtained from disposal ponds at the plant sites, placed in metal cans lined with heavy plastic bags, and transported to WES. The percent solids of Sludge A was 47.6, and the pH was 10.3. The percent solids of Sludge B was 34.2, and the pH was 9.0.

Table 2 shows the concentrations for 20 parameters for Sludges A and B. Tabulations for sludge liquor provide the allowable limits for metal concentrations from the Journal of Water Technology and Quality 75-76, Maximum Allowable Domestic Water Supply Criteria (9, 10). As noted, some of the values are secondary standards (EPA) proposed for drinking water criteria.

Characteristics

As can be noted from Table 2, the two FGD sludges are very similar in composition. Sludge A (lime-scrubbed sludge) is generally high in trace metal content and has higher concentrations of arsenic, beryllium, chromium, copper, manganese, nickel, lead, and vanadium than Sludge B. Boron and chloride levels are also higher in Sludge A than Sludge B. These variations probably reflect differences in the chemical composition of the coals burned at the two power plants. It can also be noted that Sludge B has more magnesium than Sludge A, which is probably due to the incorporation of dolomite in the limestone feed used for scrubbing. Lime usually has a lower magnesium content than scrubber limestone.

With few exceptions, the compositions of the sludge liquors are very similar. The scrubber liquor from Sludge A has more than twice the concentration of manganese than does liquor from Sludge B. The scrubber liquor from Sludge B has higher concentrations of copper, boron, cyanide, and sulfate. The liquid of both sludges contains only five chemicals or compounds in concentrations that exceed the EPA allowable limits. These are cyanide, manganese, sulfate, boron, and chloride (Table 2).

SELECTION AND PROPERTIES OF SOIL MATERIALS AND LINERS

The soil and liner materials selected for use are described in this section. Emphasis was placed on the use of admix and spray-on materials for liners. The selection of candidate liners was based on prior experience with the materials, but a screening process that included permeability testing as a basic requirement resulted in deletion of many of the materials because of very highly permeable conditions. Similar screening processes were used to

TABLE 1. CHEMICAL ANALYSIS PARAMETERS AND TEST METHODS

Parameter	Test Method	Limit of Detection (ppm)
Arsenic (As)	Atomic absorption (AA), gaseous hydride method	0.002
Beryllium (Be)	Emission spectrophotometer	0.005
Cadmium (Cd)	AA, graphite furnace	0.001
Chromium (Cr)	AA, graphite furnace	0.001
Copper (Cu)	AA, graphite furnace	0.002
Mercury (Hg)	AA, cold vapor techniques	0.0002
Magnesium (Mg)	AA, flame	0.1
Manganese (Mn)	AA, flame	0.01
Nickel (Ni)	AA, graphite furnace	0.005
Lead (Pb)	AA, graphite furnace	0.003
Selenium (Se)	AA, gaseous hydride method	0.003
Vanadium (V)	Emission spectrophotometer	0.005
Zinc (Zn)	AA, graphite furnace	0.001
Boron (B)	Standard Methods* - 107B	0.3
Chloride (Cl)	Standard Methods* - 112B	8.0
Cyanide (Cn)	Technicon autoanalyzer	0.005
Nitrite, nitrogen (NO_2, N)	Standard Methods* - 134	0.01
Nitrate, nitrogen (NO_3, N)	Standard Methods* - 213E	0.05
Sulfite (SO_3)	Standard Methods* - 158	1.0
Sulfate (SO_4)	Standard Methods* - 156C	4.0

* Standard Methods for the Examination of Water and Wastewater. 14th ed. American Public Health Association, Washington, D. C., 1976.

TABLE 2. CHEMICAL ANALYSIS OF SLUDGES AND EPA ALLOWABLE LIMITS

Parameter	Sludge A		Sludge B		EPA
	Sludge Solids (mg/kg)	Sludge Liquid (mg/ℓ)	Sludge Solids (mg/kg)	Sludge Liquid (mg/ℓ)	Allowable Limits* (mg/ℓ)
Arsenic	0.28	0.003	0.16	0.003	0.05
Beryllium	6.8	0.005	1.25	<0.005	0.011†
Cadmium	0.005	0.001	0.007	<0.001	0.01
Chromium	133.0	0.001	33.3	<0.001	0.05‡
Cyanide	--§	0.012	--	0.018	0.005
Copper	0.85	0.009	0.38	0.010	0.2**
Mercury	0.44	0.002	0.84	0.002	0.002
Magnesium	3030.0	10.1	5160.0	13.8	NA††
Manganese	84.8	2.3	43.7	0.95	0.05
Nickel	0.84	<0.003	0.38	0.003	0.1‡
Lead	1.08	<0.003	0.68	0.003	0.05
Selenium	1.38	<0.003	2.15	0.007	0.01
Zinc	135.0	0.002	278.0	0.002	5.0**
Sulfite	190.0	<1.0	200.0	<1.0	NA
Sulfate	--	1281.0	68750.0	2100.0	250.0
Boron	385.0	14.0	185.0	71.2	0.75‡‡
Chloride	1330.0	675.0	300.0	670.0	250.0**
Vanadium	162.0	--	53.0	--	NA
Nitrite, nitrogen	<0.04	<0.01	<0.04	<0.01	10.0
Nitrate, nitrogen	3.0	0.5	3.0	0.51	10.0

* From References 9 and 10.

† Freshwater aquatic life criteria.

‡ Freshwater and marine organisms criteria.

§ -- = Insufficient sample to analyze for all parameters.

** Secondary standards proposed for drinking water criteria (EPA).

†† NA = Not available.

‡‡ Irrigation criteria.

select soil types for the admix and spray-on materials. For the soil selection, permeability was a major requirement, but the soil had to have the capability of being admixed on an economical basis with a particular selected candidate material.

Selected Soil Materials

The selection of soil types for this study was primarily based on experience gained during previous investigations of soil stabilization, dust palliation, and waterproofing materials. A soil of high permeability ($>10^{-4}$ cm/sec) was considered to be the most applicable for evaluating membrane and spray-on liners in that it would permit any leakage of the liners to be readily detectable. From an economic standpoint, the high permeability soils are not suitable for the admix materials because of the high percent of admix that would be required. Hence, a less permeable (finer-grained) soil was used with the admix materials. Based on this, a silty sand was selected for evaluation of the membrane and spray-on liners and a clayey silt for evaluation of admix liners. These soil types are considered representative of typical soils that might be encountered in a disposal area.

Silty Sand--

A brown, nonplastic, silty sand with a specific gravity (G_s) of 2.68 (unified soil classification system [USCS]) was selected. The gradation curve is shown in Figure 7. The standard compaction test procedure indicated the optimum water content to be 12.7 percent and the maximum dry density to be 111 lb/ft^3 (Figure 8).

Clayey Silt--

A light brown, slightly plastic, clayey silt with a G_s of 2.71 (USCS) was selected. The gradation curve is shown in Figure 7 also. The standard compaction test procedure (11) indicated the optimum water content to be 17.3 percent and the maximum dry density to be 106 lb/ft^3 (Figure 8).

Soil Permeabilities

The permeabilities of the two soil types were determined using standard laboratory techniques (SLT) (11). These values are presented in Table 3. The permeability determined using SLT identified these two soil types further. Of more immediate importance, these values have been compared (Table 3) with the values determined using a typical test cell apparatus (TCA) described in Section 4 under conditions outlined below.

Some very important differences exist between the two test methods. The SLT procedure calls for de-aired, distilled water, whereas the TCA does not. The SLT procedure calls for an oven-dried sample that is saturated before the test begins; the TCA does not. The SLT procedure calls for the entire specimen to be vibrated to the correct thickness/density in one layer; the TCA does not. Last, the SLT procedure calls for the head to be regulated to avoid high/large hydraulic gradients; the TCA does not. These differences indicate the inherent strength and/or weakness of this particular test situation. It was the intent of this investigation to use the TCA instead of the SLT to duplicate, insofar as possible, the expected field test conditions.

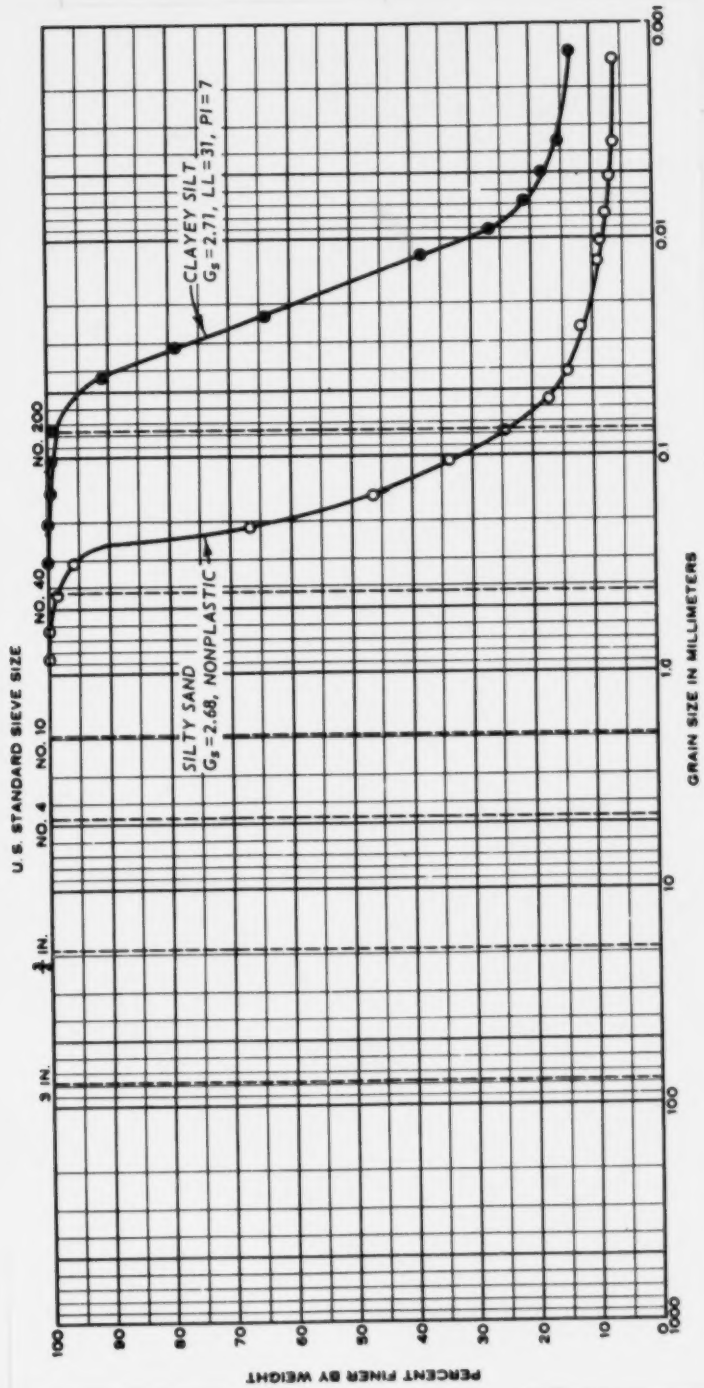
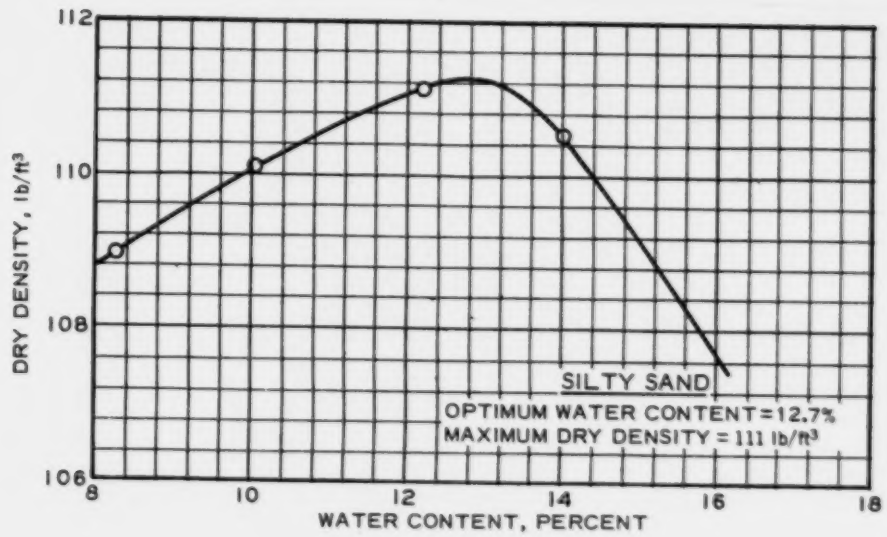


Figure 7. Gradation curves for soil materials.



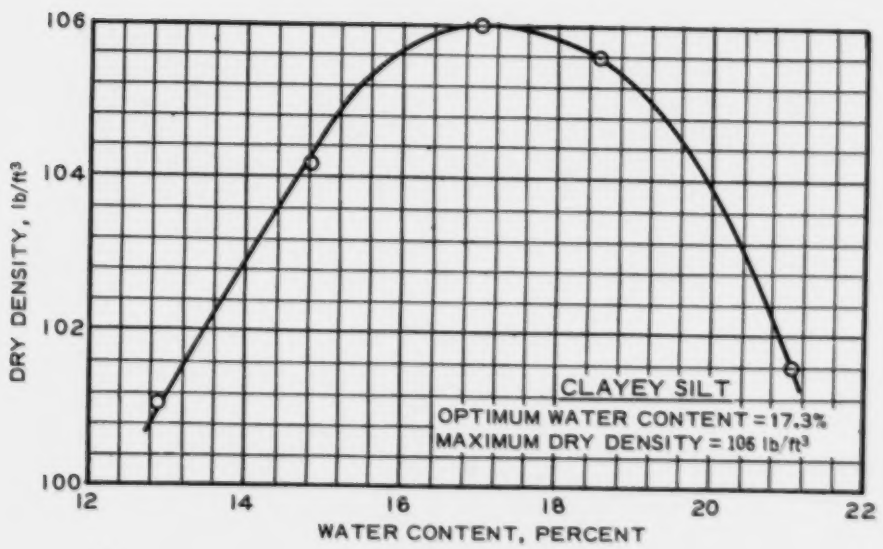


Figure 8. Moisture-density curves for test soils.

TABLE 3. SLT AND TCA PERMEABILITY VALUES

Conditions	Permeability ($cm/sec \times 10^{-6}$)
SLT Values:	
Silty sand - constant head method	460.0
Clayey silt - falling head method	0.57
TCA* Values:	
Water (only)	28,500.0
6-in. compacted silty sand, water	81.0
6-in. compacted clayey silt, water	16.0
6-in. compacted silty sand,	
5-gal Sludge A plus water	49.0
5-gal Sludge B plus water	47.0
6-in. compacted clayey silt	
5-gal Sludge A plus water	7.0
5-gal Sludge B plus water	1.0

* Test cells filled as noted, with porous plate and drain tube in place.

The permeability of a typical TCA was determined to ensure that this value was at least as great as the permeability of either test soil selected. To do this, a test cell with porous plate, drain port, and drain tube in place was filled with tap water to a level 4 in. below the top of the test cell and allowed to drain freely into a collection device. The permeability was calculated by measuring the amount collected and the time during which it was collected. (See Section 6 for other test results.) The permeability value obtained in this way (Table 3) indicated that the TCA would not interfere with subsequent similar measurements described below.

Each test soil was compacted 6 in. deep at optimum density in separate test cells (see Section 5 for compaction techniques). Each test cell was carefully filled with tap water, and the permeability was calculated and listed (Table 3). The permeability of the silty sand was almost six times less in the test cell than that determined by the SLT, whereas the clayey silt in the TCA was 28 times greater than its corresponding SLT value. The permeability value of silty sand was less when obtained in the test cell primarily because the water level was not held constant; however, the clayey silt value was greater because the soil was not saturated before testing. The test started when the water level reached 4 in. from the top of the test cell.

The TCA soil permeability values also provided an intermediate point (permeability value) for the same setup as before with sludge added. The

following test series was to determine whether the sludge/sludge liquor increased or decreased the permeability of the TCA.

Six inches of compacted silty sand was placed in each of two test cells, and 6 in. of compacted clayey silt was placed in each of two test cells. Approximately 4 gal of Sludge A was added to each of the test cells, one with compacted silty sand and one with compacted clayey silt. Approximately 4 gal of Sludge B was added to each of the remaining two test cells. Tap water was added until the liquid reached a level 4 in. below the top of each test cell and was allowed to drain freely, as before. Adding sludge to a particular test cell/compacted soil combination reduced the permeability value of that system by about half, except that the addition of Sludge B to compacted clayey silt reduced permeability to 1/16 of the original value. Actual values are listed in Table 3.

The permeability values listed in Table 3 show how each succeeding step of adding compacted soil and sludge reduced the permeability of the TCA. The table is important in that it indicates whether or not the final variable, the liner itself, was reducing the TCA permeability. Table 3 thus became the data base for all liners. Any liner in a test cell/soil/sludge system exhibiting permeability the same as or greater than that of a similar but linerless configuration in Table 3 would be closely examined and probably rejected.

Liner Selection and Testing

In the past, admix materials have been added to roadway/runway soil primarily to increase the base or subbase bearing capacity (soil strength). More recently, admix materials have found increasing use as modifiers to improve the workability of a soil or to reduce substantially its susceptibility to water. Similarly, spray-on materials are applied to control dust or prevent weathering cycles (including rainfall) from eroding the soil surface, but the more expensive, more time-consuming permeability tests normally have not been conducted. To achieve the objectives of this study, a reasonably fast method of determining permeability for various admix and spray-on materials at various application rates was needed.

The procedure used for the admix liners consisted of preparing the test specimens and compacting the material in a Harvard miniature test apparatus (12). For the spray-on liners, soil specimens were prepared and compacted in the Harvard miniature mold, and the spray-on materials were applied to the top surface of the soil specimen. Both admixed and spray-on specimens were allowed to cure for 7 days under humid conditions. Following the curing period, a rubber membrane was placed around the top of the mold to form a watertight connection to a tube. Water was introduced into the tube to provide a 2-ft constant head on the liner materials. The water permeating through the specimen was collected, measured over a known period of time, and used to determine the permeability.

A deviation from this procedure was required for screening the asphaltic concrete mix because of the size of aggregate in the mix. All admix specimens were prepared 2 in. thick by 11-5/8 in. in diameter and placed in a test cell. The test cell was filled with water, and the permeability of a particular mix

design was determined in the same manner as for the selected conditions described above and listed in Table 3.

The prefabricated membrane materials were tested for leakage (pinholes) or other abnormalities by the use of a 21-in. standpipe with a bell shape on the lower end, as shown in Figure 9. The membrane was placed on the bell end, sealed with silicone, and secured with a ring and "C" clamps. The standpipe was filled with water that was allowed to remain for an extended period of time, usually 15 to 20 days. Leakage was detected by the accumulation of moisture in a container beneath the device.

Results of the screening process and selection of liner materials are discussed as follows.

Selected Liner Materials

The items selected for exposure testing as liners in cells containing sludge are listed in Table 4.

Admix Liners--

The quantity of admix to be added to the soil for preparation of the liners was based primarily on experience with the use of admixtures to improve the strength, durability, or workability of soils in various civil engineering projects. In some cases, the admix quantity used was recommended by the admix producers. Although several tests (including permeability, density, compressive strength, penetration of asphalt, and viscosity of asphalt) were performed on the admix liners, permeability was the prime measurement used to select the percentage of an admix.

Admix materials produced by Takenaka Komuten Company (Japan) are identified as TACSS 020, TACSS 025, C400, and CST. They were included in the study based on data presented by the company that the admixtures had a high potential for creating an impermeable condition. The Takenaka Company provided the materials and personnel to assist in formulating the mixes used as liner specimens.

Asphaltic concrete-- The asphaltic concrete mix used consisted of 1/2-in.-maximum-size aggregate with an 11 percent asphalt content. The material was compacted in 2-in.-thick by 11-5/8-in.-diameter specimens for installation in the test cells. The 11 percent asphalt content is not unusual in preparing mixes for pond and canal liners where impermeable mixtures are desired.

Portland cement--Type I Portland cement, which is readily available in most areas, was selected as an admix to produce higher strength in otherwise acceptable soils. Trial applications of 6, 8, and 10 percent cement admix were prepared and subjected to permeability tests. The specimens with 6 and 10 percent admix did not leak, whereas the specimen at 8 percent had slight leakage. No reason for the slight leakage could be found, but the larger application rate of 10 percent of the dry weight was selected.

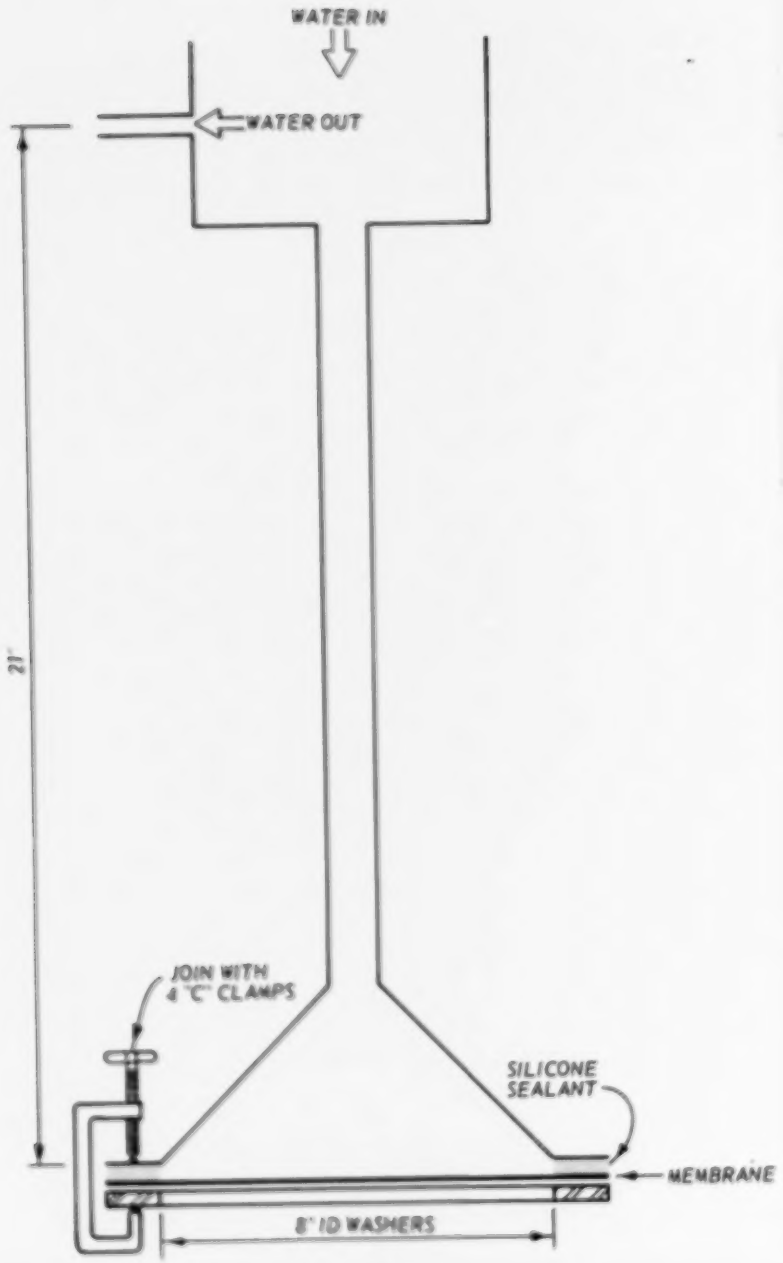


Figure 9. Pinhole test device for membrane liners.

TABLE 4. SELECTED LINER MATERIALS

ID No.	Material Name and Type*	Percent/Description/Type
	Admix Liner Material:	
12	Lime	Hydrated ASTM C 141-67†
10	Portland cement	Type I ASTM C 150-78♦
15	Cement with lime	4 percent Type I Portland cement 6 percent hydrated lime
11	M179	4 percent polymer, bentonite blend
08	Guartec UF	4 percent light gray powder
09	Asphaltic concrete	11 percent asphalt cement 1/2 in. (max.) aggregate
14	TACSS 020	6 percent blackish-brown liquid
16	TACSS 025	6 percent blackish-brown liquid
17	C400	15 percent finely ground powder
18	CST	15 percent finely ground powder
	Spray-on Liner Material:	
03	DCA-1295	3/4 gal/yd^2 polyvinyl acetate
04	Dynatech	3/4 gal/yd^2 natural rubber
05	Uniroyal	3/4 gal/yd^2 natural latex
06	Aerospray 70	3/4 gal/yd^2 polyvinyl acetate
07	AC40	3/4 gal/yd^2 asphalt cement
13	Sucoat	As-supplied molten sulphur
	Prefabricated Membrane Liner:	
01	Total Liner	As-supplied elasticized polyolefin
02	T16	As-supplied black chloroprene-coated nylon

* For manufacturer/address, see Appendix A.

† Standard Specifications for Hydraulic Hydrated Lime for Structural Purposes. In: 1978 Annual Book of ASTM Standards, Part 13, Designation: C 141-67 (rev 78). Philadelphia, Pennsylvania, 1978.

♦ Standard Specifications for Portland Cement. In: 1978 Annual Book of ASTM Standards, Part 14, Designation: C 150-78. Philadelphia, Pennsylvania, 1978.

Portland cement with lime--Lime or calcium hydroxide, commonly called hydrated lime, is readily available and can be added to soil to reduce the volume change potential and render the soil easier to compact. Although both cement and lime have been used separately in large quantities to stabilize soil, very little has been done with these two materials in combinations. It was believed that some combination of the two materials would produce the desired benefits of both materials: an increase in strength and a decrease in volume change potential. It is known that some percentage of lime (approximately 1 percent) is lost as a result of carbonation, which is the reaction of calcium with carbon dioxide in the air, so an arbitrary combination of 4 percent Type I Portland cement and 6 percent hydrated lime was selected and tested. When the test specimen failed to leak, this application rate (both percents of the dry soil rate) was accepted, and the combination of the two materials was used as one of the admix materials.

C400--The C400 material is a finely ground powder produced in Japan. It is reported to be very similar to cement with additional (unspecified) additives. A large variety of uses is well documented by the Japanese. This material was applied at 15 percent of dry soil weight following tests of 5, 10, and 15 percent.

CST--There were no apparent differences noted between the CST material and C400 described above. It was applied at the same rate as the C400.

Guartec UF--Guartec UF is a highly refined, unmodified gum produced by grinding the guar bean into a fine powder. The guar bean is a legume plant that is native to India, but it is now grown in northern Texas and southern Oklahoma. Typical properties are that it is a free-flowing powder, it has 12 percent maximum moisture, and 99 percent passes the 100-mesh screen. The bulk density (packed) is 55 lb/ft^3. It is described as having five to eight times the thickening power of starch. It was reasoned that this material would swell to fill the soil voids. The application rate of 4 percent of the dry soil weight resulted in a specimen that did not leak and that was used in the test cells.

Lime--Lime was tested and applied at the rate of 10 percent of the dry soil weight for comparison with Portland cement.

M179--M179 is a preblended mixture of water-swellable polymers and bentonite. This material has been widely used as a sealant for reservoirs, and it is reported effective in all soil types ranging from sand to clayey soils. The material was applied at the rate of 45 tons per acre (approximately 4 percent of the dry soil weight), as suggested by the supplier.

TACSS 020--TACSS 020 is a blackish-brown transparent liquid (G_s = 1.115) produced in Japan. A proprietary liquid catalyzer may be used to adjust the cure time. This material was applied at the rate of 6 percent of the dry soil weight, as suggested by the supplier.

TACSS 025--TACSS 025 is a blackish-brown liquid (G_s = 1.120) produced in Japan. A proprietary liquid catalyzer may be used to adjust the cure time. This material was also applied at the rate of 6 percent of the dry soil weight, as suggested by the supplier.

Pertinent physical data for the admix materials before subjection to the sludge (zero time data) are presented in Table 5.

Spray-on Liners--

The materials used for spray-on liners were selected primarily from those previously evaluated for dust control for military applications (13). The selection was based on experience with regard to ease of application, danger to personnel in applying or using, and subsequent behavior when exposed to climatic conditions. One material, a molten sulfur product that EPA suggested as a candidate material, was supplied by the Chevron Company in a premolded specimen made to size for installation in the test cells.

Other than the molten sulfur product, the materials were applied at a uniform rate of 3/4 gal/yd^2 based on experience gained in use for dust control. This rate was considered adequate to provide complete coverage and preclude thin areas where pinholes or air bubbles might develop, yet it was an insufficient quantity to flow (experience indicates that greater application tends to flow).

The spray-on liners were subjected to permeability, density, and tensile strength/elongation tests. Pertinent physical data for the spray-on liner material for zero time are presented in Table 6. Figure 10 shows a typical spray-on material (AC40) being cured in the laboratory. All spray-on materials were cured for zero time physical testing in a similar fashion.

AC40--AC40 is an asphalt material refined to meet specifications for paving, industrial, and special purposes. Specifications for this material require a viscosity of 4000 ± 800 poises at a temperature of 135°C (275°F) and a penetration of 200 (minimum) at 25°C (77°F) for 100 g for 5 sec. This material requires a high temperature to flow (300° to 400°F), and it was applied at the rate of 3/4 gal/yd^2.

Aerospray 70--Aerospray 70 is a polyvinyl acetate material weighing about 9.2 lb/gal. This liquid is white and cures to form a clear, flexible film. The application rate was 3/4 gal/yd^2. This material has been used to control erosion in areas of new vegetation.

DCA-1295--DCA-1295 is similar to Aerospray 70, but it contains additional plasticizers and other additivies to increase shelf life and help produce a more flexible film. The application rate was 3/4 gal/yd^2. This material was developed to control dust during military operations.

Dynatech--Dynatech is a natural rubber latex compound designated 1-H-10 formulation No. 267. It was applied at a rate of 3/4 gal/yd^2. An experimental product, it is one of the materials considered for the military dust control program.

Sucoat--Sucoat is a molten sulfur product that is placed at high temperature (300° to 400°F) and forms a strong solid upon curing. Four 3/8-in.-thick discs, approximately 11-5/8 in. diameter, were supplied by the manufacturer for testing, and they were installed in the cells as received. This is a new product described as a quick setting, watertight, coating compound.

TABLE 5. PHYSICAL TEST DATA FOR ADMIX LINERS AT ZERO TIME
(Control Data)

ID No.	Liner Material	Application* Rate (%)	Water Content (%)	Dry Density lb/ft^3	Height / Diameter H/D	Axial Strain ΔH/H (%)	Unconfined Compression† $lb/in.^2$
	Clayey silt	NA#	16.6	103.5	2.051	3.1	38.4
08	Guartec UF	4	17.4	90.0	2.042	5.9	13.9
10	Portland cement	10	16.6	102.8	2.155	1.0	663
11	M179	4	13.2	103.9	2.009	NA	<5
12	Lime	10	17.3	101.0	2.153	1.0	242
14	TACSS 020	6	16.2	106.3	2.154	6.3	179
15	Portland cement plus lime	4, 6	16.1	104.1	2.172	1.0	503
16	TACSS 025	6	16.4	104.6	2.173	5.0	164
17	C400	15	15.9	105.4	2.111	1.0	721
18	CST	15	14.4	105.2	1.792	1.0	1160

ID No.	Liner Material	Application* Rate (%)	Asphalt Content (%)	Penetration (0.1 mm)	Viscosity (poises)
09	Asphaltic concrete	11% asphalt 1/2-in. aggregate	10.4	60	2959

* The application rate is based on the percent of dry soil weight or dry aggregate weight.

† UC tests followed 7 days of humid cure.

NA = Not available.

TABLE 6. PHYSICAL TEST DATA FOR SPRAY-ON AND MEMBRANE LINERS AT ZERO TIMES
(Control Data)

ID No.	Liner Material	Thickness (in.)	Weight (g)	Density (lb/ft^3)	Application Rate (lb/yd^2)	Apparent Elongation (%)	Breaking Strength (lb)
01	Total Liner	0.023	7.77	54.58	0.92	136	544
02	T16	0.018	8.95	75.75	1.04	26	482
03	DCA-1295	0.219	112.44	81.42	13.42	172	127
04	Dynatech	0.093	29.98	55.50	3.87	486	128
05	Uniroyal	0.111	35.39	53.45	4.43	615	122
06	Aerospray 70	0.158	80.77	82.27	9.74	235	106
13	Sucoat*	--	--	--	--	--	--

		Asphalt Content	Penetration (0.1 mm)	Viscosity (poises)
07	AC40	NA†	49	8237

* Four discs 3/8 in. thick were received from the manufacturer. All four were used in the test cells, but test data was insufficient.

† NA = Not available.

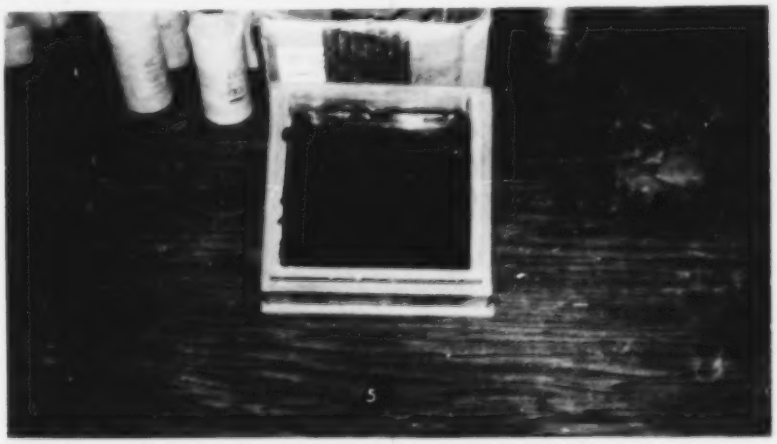


Figure 10. AC40 curing in a plastic mold. All spray-on materials were cured in a similar fashion for physical testing at zero time.

Uniroyal--Uniroyal is a black, natural latex designated L9241 by the manufacturer. It was applied at the rate of 3/4 gal/yd^2. This experimental product was one of the materials that passed the traffic phase of the dust control program.

Prefabricated Membrane Liners--

The following prefabricated liners were selected for evaluation and were subjected to permeability, density, and tensile strength/elongation tests. Pertinent physical data for prefabricated membrane liner material for zero time are presented in Table 6.

Total Liner--Total Liner is an elasticized polyolefin approximately 20 mils thick. The membrane was applied as received. This material was furnished by the manufacturer at the request of the EPA.

T16--T16 is a chloroprene-coated nylon approximately 18 mils thick. This composite material is formed from a single-ply nylon fabric coated with neoprene and weighs 18.5 oz/yd^2. This membrane was developed at WES as an expedient airfield pavement surfacing material. The membrane was applied as received from the producer.

SECTION 5

PROCEDURES FOR PREPARATION AND INSTALLATION OF LINER AND SLUDGE MATERIALS IN TEST CELLS

GENERAL PROCEDURES

The sequence for fabrication of the test cells was basically the same for all cells and followed the routine presented in Section 4. The method of preparing and installing the liners is discussed in this section. Since compaction of the soil materials (and liners in the case of admix materials) was a pertinent part of the preparation of all of the liner/cell combinations, the details of the procedure are presented initially to obviate further discussion for individual liner types.

COMPACTION DEVICES AND METHODS

Compaction devices consisting of two different-sized footings were prepared for the Instron machine (Figure 11). These devices were used to statically compact soil in the test cells in 2-in.-thick layers. The surface of the compacted layer was scarified, and another layer was added. In this manner, three layers of a predetermined weight of soil were compacted using a procedure that closely parallels the one used in preparing Harvard miniature specimens (Figure 12). Finally, an 11.5-in.-diameter compaction foot was attached to the Instron machine, and the soil surface was leveled throughout to a 6-in. depth, assuring the desired optimum density. The footings were mounted on shafts of sufficient length to reach the lowest part of the cell.

LINER PREPARATION

Admix Liners

The admix-type liners were prepared in accordance with the proportions discussed in Section 4. Each admix material was thoroughly mixed with the clayey silt, placed in a test cell, and compacted; then liners were allowed to cure for 7 days at 78°F and 50 percent humidity. The only deviation was the asphaltic concrete, which was prepared separately in a special mold with the same diameter as the test cell. This procedure was necessary to obtain sufficient density of the mix during compaction and also to prevent any damage to the underlying silty sand on which it was placed. This operation resulted in a 2-in. thickness of asphaltic concrete over a 6-in. layer of compacted

Figure 11. The Instron machine with both compaction footings.

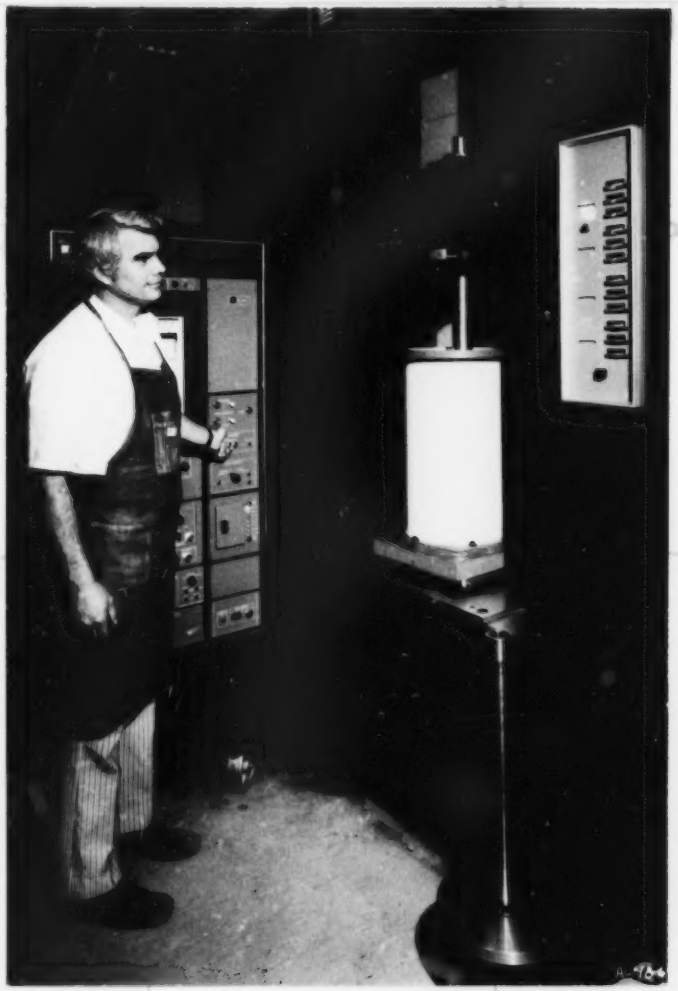


Figure 12. Typical operation using Instron machine and 4.5-in.-diam footing to compact soil layer in a test cell.

silty sand. This was the only admix material used in conjunction with the silty sand soil. All others were mixed with the clayey silt soil and compacted in a test cell.

Spray-on Liners

The spray-on liner materials were applied to the surface of the silty sand soil. The silty sand was compacted 6 in. deep in the test cell at optimum moisture and density and was allowed to cure (normally 2 to 3 days) at 78°F and 50 percent humidity. The spray-on materials were placed on the surface (3/4 gal/yd^2) and allowed to cure in accordance with the manufacturer's recommended time. The cure time was usually about 4 hours or less.

Prefabricated Membrane Liners

The prefabricated membrane liners were prepared to include a seam or joint in the midportion of the specimen, which was then cut to the diameter of the test cell. The seam was considered to be a necessary part of the test, as one would certainly be encountered in covering a large area. The liners were placed on 6 in. of compacted silty sand in the test cell.

SEALANT

A silicone sealant was used to seal around the periphery of the liner and test cell wall. To obtain the best results possible, the sealant was used with a primer, which was placed only on the PVC test cell walls in bands approximately 3 in. wide in the area where the sealant would be placed. The sealant formed a triangular-shaped wedge that extended approximately 1 in. out on the liner and 1 in. up the test cell wall. The sealant was allowed to cure until it was dry to the touch.

FGD SLUDGE

The FGD sludges were collected and transported in metal cans lined with heavy vinyl bags. Before placement in the cells, the sludge was thoroughly mixed using a portable mixer with extended mixing blades (Figure 13). After they were mixed, the sludges were added to the test cells at a rate of approximately 4 gal per test cell.

CHEMICAL ANALYSIS DATA BASE

A chemical analysis of the sludge solids and sludge liquids was conducted on both Sludges A and B as received. The analysis included measurement of the concentration in mg/ℓ for 20 parameters (Table 7) and further identification of the sludges used (see Section 4 and Table 2). The establishment of a chemical analysis data base for each different testing situation was also considered desirable. Therefore, a chemical analysis was conducted on the leachate from unlined test cells loaded as follows:

Lab Symbol	Sludge Type	Soil Type
1-100	A	Clayey silt
2-100	A	Silty sand
1-400	B	Silty sand
2-400	B	Clayey silt

Figure 13. Portable mixer with extended mixing blades.

TABLE 7. CHEMICAL ANALYSIS OF LEACHATE FROM UNLINED TEST CELLS AND EPA ALLOWABLE VALUES (mg/ℓ)

Parameter	Sludge A		Sludge B		EPA Allowable Values (9, 10)
	Sand (2-100)	Clay (1-100)	Sand (1-400)	Clay (2-400)	
Arsenic	0.003	0.002	0.004	0.004	0.05
Beryllium	0.005	0.005	0.005	0.005	0.11*
Cadmium	0.002	0.002	0.003	0.003	0.01
Chromium	0.001	0.001	0.001	0.001	0.05
Cyanide	0.029	0.01	0.034	0.01	0.005†
Copper	0.013	0.001	0.003	0.003	0.2†
Mercury	0.0002	0.0002	0.0002	0.0002	0.002
Magnesium	65.1	22.2	74.1	20.0	NA‡
Manganese	0.01	0.35	0.01	0.01	0.05
Nickel	0.005	0.005	0.005	0.005	0.1*
Lead	0.006	0.010	0.005	0.005	0.05
Selenium	E§	E	E	E	0.01
Zinc	0.020	0.020	0.016	0.026	5.0**
Sulfite	1.0	1.0	1.0	1.0	NA
Sulfate	241.0	42.0	297.0	36.0	250.0**
Boron	14.7	1.1	7.4	0.6	0.75††
Chloride	83.0	95.0	78.0	79.0	250.0**
Vanadium	0.021	0.005	0.018	0.005	NA
Nitrite, nitrogen	14.3	0.01	31.6	0.001	10.0
Nitrate, nitrogen	75.6	0.33	47.5	0.05	10.0

* Freshwater aquatic life criteria.

† Freshwater and marine organisms criteria.

‡ NA = Not available.

§ E = equipment being repaired.

** Secondary (EPA) standards proposed for drinking water criteria.

†† Irrigation criteria.

COMPLETION OF ASSEMBLY

The top plates were attached, and the cells were placed in the holding area. The pressurization system was installed and attached to the cells. The system for collection of the leachate was assembled, and the exposure test was begun. Following the first month of 0 psig (atmospheric pressure), the pressure system was activated and the pressure was increased to 2 psig, simulating placement of approximately 3 ft of sludge. Similarly, the pressure was increased 2 psig each month for a total of 10 months (30 ft of head or 20 psi). A disposal area with less than a 1-year capacity probably would not be economically feasible, yet half of the test cells would be removed after only 12 months, and it seemed desirable to have some portion of that period at the full design condition (i.e., 30 ft of head).

IDENTIFICATION SYSTEM

A method to identify the test cell sludge/liner combination was developed. Each liner material was assigned a number from 01 to 18; these two numbers were followed by either a 1 (for 12 months of exposure time) or a 2 (for 24 months of exposure time); finally, this number was followed by a letter (A for Sludge A, or B for Sludge B). Thus each test cell was assigned an identification number, and all particulars were noted on a master sheet. For example, 121B on a test cell indicates that the liner is lime, the test duration is 12 months, and the sludge is "B" (FGD sludge from an eastern coal limestone-scrubbed process).

SECTION 6

RESULTS

TWELVE-MONTH TEST DATA

At the end of the first 12-month period, 36 test cells were depressurized at the rate of 2 psig per hour and removed from the holding areas for disassembly. All remaining liquid and sludge solids were removed from the liner in a way that would not damage the liner or test cell.

Physical Tests

Admix Liner Materials--

Admix liner materials were removed for testing by coring with a 3-in.-OD, diamond-studded, hollow-core bit. It was necessary to core each admix liner three times to help ensure duplicate test specimen values for each situation (test cell) because it was not possible to determine if a cored sample sheared during coring. Shearing was not immediately detectable for two reasons: (a) no discernible differences could be noted in the coring machine operation when shearing occurred, and (b) the test cell had to be transported to an area where the baseplate could be removed and the cored samples extracted. Since the bit was not allowed to penetrate the 6-in. soil layer more than 5-3/4 in. (to prevent damage to the baseplate), the baseplate had to be removed and 1/4 in. of the soil scraped away before the cored specimen could be removed and examined (Figure 14). Each specimen was trimmed as necessary for the UC test, and the specimen was measured, weighed, and tested. Water contents were determined after testing in UC (Figure 15). These values and any pertinent observations are listed in Table 8. The zero time data for each liner are also presented in Table 8 for ease of comparison.

Nine of the admix liner materials were handled in this fashion. The tenth admix liner material, asphaltic concrete, was cored, and the asphalt material was extracted (from the aggregate added initially and whatever infiltrated the liner). The percent asphalt was determined, and the asphalt was examined for penetration and viscosity values. These data are listed in Table 8 with the corresponding zero time values.

Spray-on and Prefabricated Membrane Liners--

Following depressurization and the liquid/sludge removal above the spray-on and prefabricated membrane liner material, the silicone edge sealer was peeled from the test cell wall, and in the case of the prefabricated membranes, the liners were rolled back and removed from the cells. This procedure

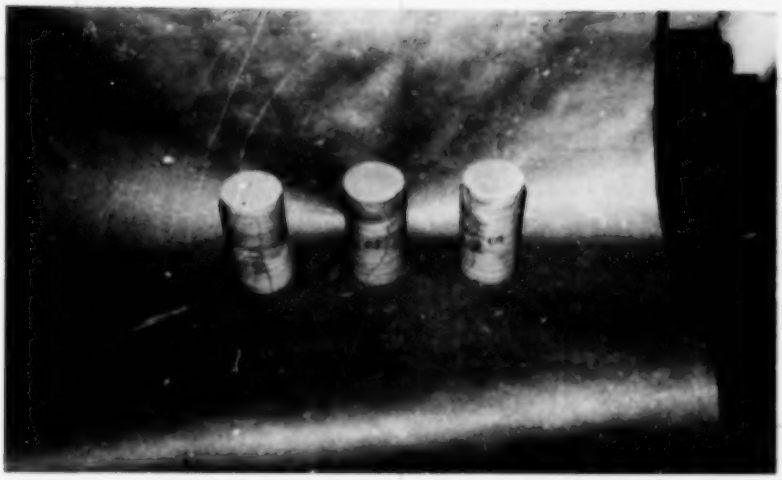
Figure 14. Soil being removed from bottom of test cell lined with TACSS 025.

was somewhat more difficult with the spray-on liners, because the liquid penetrated the soil surface and formed a film that bonded to the soil. However, with care, it was possible to remove the spray-on liner from the soil surface. Gentle washing of the spray-on liner with aerated tap water removed the remaining loose soil particles and the sludge solids. Some soil particles were completely encapsulated and became part of the liner, and probably other soil particles/sludge solids not so completely bound resisted the cleaning efforts described above; but no further attempts were made to dislodge them for fear of inadvertently damaging the liner itself. The washed samples were cut into 4- by 6-in. grab test samples, measured (thickness) and weighed, and kept under tap water until 4 hours or less before the time of the actual grab test. These results are presented in Table 9.

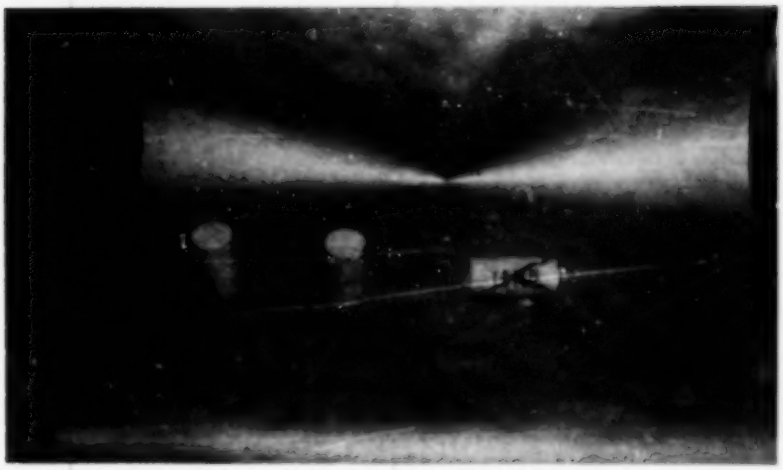
Five of the spray-on and the two prefabricated membrane liners were handled in this fashion. The AC40 spray-on material formed a highly flexible film that could not be tested by the grab test method. Since the AC40 is an asphalt material, samples of it were taken, and the asphalt content, penetration, and viscosity values were determined (Table 9).

Permeability

Each test cell had its own collection system (see Figure 3), and any leachate from a test cell would exit through the drain port and proceed via plastic tubing to a plastic container. Each container was checked regularly, and the contents were noted for several reasons. First, even though a liner material might prove permeable, the permeability might be so low that the environment would remain essentially unaffected. Second, a permeable liner material could be a very effective filter and the chemical analysis of the leachate could show it to be of no consequence to the environment.



a. Portland cement.



b. TACSS 020

Figure 15. Admix liner materials following 12 months of inundation and UC testing.

TABLE 8. PHYSICAL TEST RESULTS FOR ADMIX LINERS AFTER 12 MONTHS

ID No.	Liner Material	Application Rate ($)	Water Content ($)	Dry Density (lb/ft^3)	Sample Height / Diameter	Axial Strain (ΔH/H, $)	Unconfined Compression (lb/in.^{2})	Permeability (10^{-6} cm/sec)	Remarks
00A	Clayey silt	NA*	16.6	103.5	2.051	3.1	38.4	7.0	Untreated soil - treated following 7 days humid cure.
00B		NA	16.7	103.5	2.051	3.1	38.4	1.0	
080†	Quartec UF	4	17.4	90.9	2.042	5.9	13.9	--	Eight test cells attempted - all leaked. Horrible odor developed, probably indicative of material breakdown. Liner material poured from test cell - rejected. Too soft to test. All tests discontinued.
081A*		--	--	--	--	--	--	0.117	
081B*		--	--	--	--	--	--	--	
100†	Portland cement	10	16.6	102.8	2.155	1.0	663		Very hard to core samples. Silicone seal bond was poor.
101A			21.0	103.0	2.094	1.0	1779		
101B			20.3	103.6	2.111	1.0	1893		
110†	M179	4	13.2	103.9	2.009	NA	<5		Same as Quartec above. All tests were discontinued.
111A								0.156	
111B								0.084	
120†	Lime	10	17.3	101.0	2.153	1.0	242		Very hard to core samples. Silicone seal bond was poor.
121A			20.1	100.8	2.073	1.0	1294		
121B			22.3	101.7	2.073	1.0	1200		
140†	TACSS 020	6	16.2	106.3	2.154	6.3	179		Very hard to core samples.
141A			16.7	105.9	2.153	6.6	148		
141B			16.5	105.9	2.159	6.3	162		
150†	Portland cement plus lime	4	16.1	104.1	2.172	1.0	503		Back pressure of 2 psi failed to produce any bubbles that would indicate leaks. Silicone seal bond was poor.
151A		6	20.4	103.7	2.118	1.0	1297		
151B			20.1	104.4	2.063	1.0	1496		
160†	TACSS 025	6	16.4	104.6	2.173	5.0	164		
161A			17.1	104.8	2.157	7.0	147		
161B			18.3	104.0	2.160	7.0	144		
170†	C400	15	15.9	105.4	2.111	1.0	721		Very hard to core samples.
171A			20.3	104.2	2.106	1.0	1510	none	
171B			19.8	105.6	2.171	1.0	1294	0.003	
180†	CST	15	14.4	105.2	1.792	1.0	1160		Very hard to core samples.
181A			19.0	106.2	2.118	1.0	1792	0.011	
181B			19.9	105.3	1.953	1.0	2091	0.004	

		Asphalt Content ($)	Penetration (0.1 mm)	Viscosity (poises)	Permeability (10^{-6} cm/sec)	
090†	Asphaltic concrete	10.4	60	2959		
091A	11$ asphalt	11.2	68	3749		Silicone seal questionable.
091B	1/2-in. aggregate	10.3	62	2945		Silicone seal poor.

* NA = not available.

† 0 = Control data (zero time).

* Too soft to test.

TABLE 9. PHYSICAL TEST RESULTS FOR THE SPRAY-ON AND MEMBRANE LINERS AFTER 12 MONTHS

ID No.	Liner Material	Thickness (in.)	Weight (g)	Density (lb/ft^3)	Application Rate (lb/yd^2)	Apparent Elongation (%)	Breaking Strength (lb)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
000A	Silty sand	NA*	NA	111.0	NA	NA	NA	49.0	Untreated soil.
000B		NA	NA	111.0	NA	NA	NA	47.0	
010†	Total Liner	0.023	7.77	54.58	0.92	136	544		Leakage apparently developed between liner and sealant along 1/2-in. strip.
011A		0.022	9.10	63.66	1.07	573	158		
011B		0.025	9.80	62.98	1.15	464	134		
020†	T16	0.018	8.95	75.75	1.04	26	482		Leakage developed in two places between liner and sealant. Total length of leaking strip approximately 1/2 in.
021A		0.018	15.38	88.77	1.77	25	345		
021B		0.017	16.62	94.35	1.95	28	374		
030†	SCA-1295	0.219	112.44	81.62	13.42	172	127		The liner was discolored and apparently dissolving from chemical attack; two small holes at liner edge; liner very thin elsewhere.
031A		0.177	65.14	88.95	7.76	95	47	0.368	
031B		0.103	34.08	55.40	4.06	52	22	0.066	
040†	Dynatech	0.093	29.98	55.50	3.87	486	128		Liner and sealer separated and leak developed, although sealer/cylinder bond was good.
041A		0.100	40.79	64.23	4.79	496	82		
041B		0.113	41.99	58.72	4.95	521	118		
050†	Uniroyal	0.111	35.39	53.45	4.43	615	122		
051A		0.088	34.31	60.83	4.04	584	68	none	
051B		0.086	32.93	60.26	3.89	607	70		Liner and sealer separated.
060†	Aerospray 70	0.158	80.77	82.27	9.74	235	106		Liner badly discolored and very thin in spots, apparently as a result of chemical attack.
061A		0.071	38.61	83.11	4.36	174	37	0.034	
061B		0.096	96.00	165.88	11.34	55	34	0.040	
130†	Duncoat	NA	NA	NA	NA	NA	NA		Four discs 3/8-in. thick received from manufacturer. All four used in test cells. Silicone seal bond poor.
131A		0.420	320.83	120.32	37.88	6	225		
131B♦		--	--	--	--	--	--		

		Asphalt Content (%)	Penetration (0.1 mm)	Viscosity (poises)	Permeability ($cm/sec \times 10^{-6}$)	
070†	AC40	NA	49	8,237		
071A		19.5	42	14,752	0.067	Leaked near center of liner. No leaks around sealant. Liner ruined when removed.
071B		27.6	42	13,644	0.105	

* NA = not available.

† 0 = control data (zero time).

♦ Liner shattered when test cell ruptured under pressure.

The coefficient of permeability for each liner material, k, was approximated using the formula $Q = kiAt$, where Q is the quantity of leachate collected, A is the area of the liner material exposed (for simplicity, the gross sectional area of the test cell was used, diameter = 11-13/16 in.), t is the time period in which leakage was collected, and i is the average hydraulic gradient during the time period t. The permeability values are tabulated in Tables 8 and 9.

Filterability

To assess the gross effects of liner behavior and liner composition on the liquid first released from a lined or unlined sludge test cell (permeated water), the first 32 oz of liquid issuing from each test cell was collected and analyzed chemically. Since duplicate test cells had been constructed for each liner, duplicate samples were available for each membrane type that passed liquid. The samples were collected over varying lengths of time, but care was taken to avoid contamination of samples with dust or evaporation by using narrow-necked plastic bottles with close-fitting collection tubes. Each sample was submitted for analysis as soon as 32 oz had been collected. The methods of chemical analysis are listed in Table 1. The chemical analyses of samples are given in Tables 10 and 11. Conductivity and pH values for the samples are shown in Table 12.

These initial liquid samples (permeate water) consisted of a mixture of soil pore water, material from the liners, and sludge liquor (the liquid that is a result of and saturated with the FGD sludges). Factors that affected the composition of the initial permeate water samples were the following:

a. Initial composition of the pore water in the soil.

b. Composition of any water added to the soil during the application of the liner material to be tested.

c. Composition of the sludge liquor.

d. Composition of material leached from or generated by the decomposition of the liner material.

e. Degree of mixing of soil pore water and permeating sludge liquor in the water sample.

The soil pore water had considerable effect on the permeate composition. Approximately 0.4 ft^3 of soil (40 to 50 lb) was used in each test cell. Moisture contents for the soils as used were between 13 and 17 percent by weight. Each soil sample, therefore, initially contained 96 to 128 oz of water. Two different soil samples were used. The composition of the pore water in the soils is best shown in the initial sample taken from linerless test cells (see Table 7).

During the installation of some spray-on or admix liners, more water was added to the soil. Part of this liquid was also expelled in the first 32-oz sample submitted for analysis. The composition or amount of additional water

TABLE 10. CHEMICAL ANALYSIS OF FIRST 32 OZ OF SLUDGE A LEACHATE FROM LINED AND UNLINED TEST CELLS (mg/ℓ)

Liner Material	ID No.	Arsenic As	Beryllium Br	Cadmium Cd	Chromium Cr	Cyanide Cn	Copper Cu	Mercury Hg	Magnesium Mg	Manganese Mn	Nickel Ni
No liner (sand)	2-100	0.003	<0.005	0.002	<0.001	0.029	0.013	<0.0002	65.1	<0.01	<0.005
Total Liner	011A	<0.002	<0.001	<0.001	0.001	<0.005	0.003	<0.0002	82.4	<0.01	<0.005
	012A	0.007	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	108.5	19.3	0.022
T16	021A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	111.3	15.3	0.019
	022A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	103.4	<0.01	<0.005
DCA-1295	031A	<0.002	<0.005	<0.001	<0.001	0.010	<0.001	<0.0002	94.0	0.13	<0.005
	032A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	123.8	<0.01	<0.005
Dynatech	041A	0.004	<0.001	<0.001	<0.001	0.055	<0.002	<0.0002	161.4	7.6	0.035
	042A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	144.4	8.1	0.021
Uniroyal	051A	<0.002	<0.001	0.040	<0.001	<0.005	<0.002	<0.0002	83.3	8.0	0.019
	052A	<0.002	<0.005	<0.001	<0.001	<0.010	0.001	<0.0002	106.0	0.06	<0.005
Aerospray 70	061A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0008	111.2	<0.01	<0.005
	062A	?*									
AC40	071A	<0.002	<0.001	<0.001	<0.001	<0.005	0.002	0.0004	95.7	<0.01	<0.005
	072A	*<0.002†*	*<0.005*	*0.003*	*0.006*	*<0.005*	*<0.002*	*<0.0002*	*99.2*	*<0.01*	*<0.005*
Asphaltic concrete	091A	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	167.0	10.6	0.023
	092A	?									
Sucoat	131A	<0.002	<0.005	<0.001	<0.001	CI#	0.001	<0.0002	100.0	<0.01	<0.005
	132A	<0.002	<0.005	<0.001	<0.001	CI	0.002	<0.0002	88.4	<0.01	<0.013
No liner (clay)	1-100	0.002	<0.005	0.002	<0.001	<0.01	<0.001	<0.0002	22.2	0.35	<0.005
Guartec UF	081A	<0.002	<0.001	0.042	0.056	CI	0.500	<0.0002	1431.0	1955.0	4.23
	082A	<0.002	<0.001	0.045	0.038	0.045	0.550	0.0002	1259.0	1788.0	3.46
Cement	101A	0.004	<0.005	<0.001	0.966	0.034	0.003	<0.0002	<0.10	<0.01	<0.005
	102A	0.003	<0.005	<0.001	0.769	0.079	0.015	<0.0002	<0.10	<0.01	<0.005
M179	111A	<0.002	0.010	<0.001	<0.001	<0.005	<0.002	<0.0002	101.5	1.3	0.025
	112A	<0.002	0.003	<0.001	<0.001	<0.005	<0.002	<0.0002	94.3	3.6	0.038
Lime	121A	<0.002	0.010	<0.001	0.015	0.048	0.013	<0.0002	<0.10	0.01	0.044
	122A	<0.002	<0.001	<0.001	0.029	0.065	0.015	0.0030	<0.10	0.01	0.044
TACSS 020	141A	0.002	0.008	0.004	<0.001	0.045	<0.002	<0.0002	263.3	23.8	0.025
	142A	<0.002	0.010	<0.001	<0.001	<0.005	<0.002	<0.0002	206.5	14.6	0.046
Portland cement plus lime	151A	0.004	0.011	<0.001	0.012	<0.005	0.030	<0.0002	<0.01	<0.01	0.052
	152A	0.002	<0.001	<0.001	0.042	0.035	0.014	<0.0002	<0.10	<0.01	0.042
TACSS 025	161A	0.002	0.013	<0.001	<0.001	<0.005	0.002	<0.0002	271.0	28.9	0.033
	162A	0.014	0.011	<0.001	<0.001	<0.005	<0.002	<0.0002	280.3	44.4	0.033
C400	171A	?									
	172A	*0.111*	*<0.005*	*0.0004*	*1.229*	*0.059*	*0.294*	*0.0002*	*<0.1*	*<0.01*	*0.007*
CST	181A	<0.002	0.012	<0.001	<0.001	0.151	0.093	<0.0002	<0.01	0.01	0.058
	182A	0.003	<0.005	<0.001	<0.019	0.150	0.188	<0.0002	<0.10	0.01	0.120
EPA allowable values (9, 10)	--	0.05	0.11§	0.01	0.05	0.005#	0.2**	0.002††	NA‡‡	0.05	0.1§

(Continued)

TABLE 10. (Continued)

Liner Material	ID No.	Lead Pb	Selenium Se	Zinc Zn	Sulfite SO_3	Sulfate SO_4	Boron B	Chloride Cl	Vanadium V	Nitrogen Nitrite NO_2, N	Nitrogen Nitrate NO_3, N
No liner (sand)	2-100	0.006	E§§	0.020	<1.0	241.0	14.7	83.0	0.021	14.3	75.6
Total Liner	011A	0.01	<0.003	<0.001	<1.0	210.0	0.3	52.5	0.016	<0.01	18.0
	012A	<0.003	<0.003	0.002	<1.0	1320.0	5.8	150.9	0.035	<0.01	<0.05
T16	021A	0.014	<0.003	<0.001	1.0	1420.0	5.9	202.6	0.029	<0.01	<0.05
	022A	<0.003	<0.003	<0.001	<1.0	442.0	0.4	221.5	0.018	<0.01	0.15
DCA-1295	031A	0.019	E	0.003	<1.0	371.0	1.4	209.0	0.020	<0.01	0.30
	032A	<0.003	<0.003	0.007	<1.0	624.0	0.6	170.0	0.016	<0.01	8.7
Dynatech	041A	<0.003	<0.003	0.001	1.0	1330.0	0.4	192.0	0.030	<0.01	<0.05
	042A	0.018	<0.003	0.001	<1.0	1190.0	6.6	236.3	0.038	<0.01	1.14
Uniroyal	051A	0.005	0.009	<0.001	<1.0	1430.0	5.5	204.7	0.031	<0.01	<0.05
	052A	0.008	E	0.008	<1.0	346.0	<0.3	148.0	0.025	<0.01	0.22
Aerospray 70	061A	<0.003	<0.003	<0.001	<1.0	400.0	<0.3	108.8	0.011	0.15	5.0
	062A										
AC40	071A	0.008	<0.003	0.017	<1.0	218.0	<0.3	62.2	0.012	<0.01	<0.05
	072A	*0.003*	*0.015*	*<0.001*	*5.0*	*226.0*	*1.2*	*79.0*	*<0.005*	*0.12*	*8.2*
Asphaltic concrete	091A	<0.003	<0.003	0.004	<1.0	1080.0	6.5	460.5	0.040	<0.01	0.12
	092A										
Sucoat	131A	<0.003	E	0.004	<1.0	615.0	<0.3	66.0	0.020	<0.01	<0.05
	132A	<0.003	E	<0.001	<1.0	568.0	0.6	63.0	0.015	0.02	0.06
No liner (clay)	1-100	0.010	E	0.020	<1.0	42.0	1.1	95.0	<0.005	0.01	0.33
Guartec UF	081A	0.074	<0.003	3.45	12.0	68.0	6.5	1495.0	0.410	CI	CI
	082A	0.095	<0.003	2.86	18.1	7.6	36.5	739.0	0.521	CI	CI
Cement	101A	<0.003	E	<0.001	6.0	1079.0	<0.3	127.0	0.056	0.03	<0.05
	102A	0.017	E	0.001	<1.0	7.0	<0.3	156.0	<0.005	0.53	0.20
M179	111A	0.005	<0.003	0.005	<1.0	1420.0	2.5	525.4	0.023	<0.01	0.38
	112A	<0.003	<0.003	0.004	<1.0	1430.0	3.4	348.1	0.026	<0.01	0.12
Lime	121A	<0.003	0.003	0.004	3.0	13.0	<0.3	32.1	<0.005	0.59	<0.05
	122A	<0.003	<0.003	0.004	4.0	>4.0	0.4	57.3	<0.005	1.00	0.42
TACSS 020	141A	<0.003	<0.003	<0.001	<1.0	460.0	2.8	485.3	0.042	<0.01	0.10
	142A	<0.003	<0.003	<0.001	<1.0	320.0	<0.3	504.3	0.033	<0.01	<0.05
Portland cement plus lime	151A	0.098	<0.003	<0.001	<1.0	<4.0	<0.3	10.6	0.040	<0.01	0.12
	152A	<0.003	<0.003	0.002	5.0	>4.0	0.4	23.3	<0.005	0.95	0.14
TACSS 025	161A	<0.003	<0.003	<0.001	3.6	640.0	4.6	490.6	0.053	<0.01	0.32
	162A	<0.003	<0.003	<0.001	2.4	620.0	4.6	356.6	0.054	<0.01	0.38
C400	171A										
	172A	*0.068*	*0.161*	*0.004*	*8.5*	*3400.0*	*2.9*	*326.0*	*0.203*	*0.19*	*<0.05*
CST	181A	<0.003	<0.003	<0.001	<1.0	6.0	<0.3	33.8	0.024	0.01	<0.05
	182A	<0.003	<0.003	0.006	<1.0	16.0	0.6	42.7	0.008	0.46	0.09
EPA allowable values (9, 10)	--	0.05	0.01	5.0**	NA	250.0**	0.75††250.0**		NA	10.0	10.0

* ? = Insufficient leakage to date (<<32 oz).
† Entries shown in script are 24-month data.
‡ CI = Chemical insufficient.
§ Freshwater aquatic life criteria.
# Freshwater and marine organisms criteria.
** Secondary standards proposed for drinking water criteria (EPA).
†† Irrigation criteria.
‡‡ NA = Not available.
§§ E = Equipment being repaired.

TABLE 11. CHEMICAL ANALYSIS OF FIRST 32 OZ OF SLUDGE B LEACHATE FROM LINED AND UNLINED TEST CELLS (mg/ℓ)

Liner Material	ID No.	Arsenic As	Beryllium Be	Cadmium Cd	Chromium Cr	Cyanide Cn	Copper Cu	Mercury Hg	Magnesium Mg	Manganese Mn	Nickel Ni
No liner (sand)	1-400	0.004	<0.005	0.003	<0.001	0.034	0.003	<0.0002	74.1	<0.01	<0.005
Total Liner	011B	<0.002	<0.001	<0.006	<0.001	<0.005	0.002	<0.0002	136.5	0.4	0.015
	012B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	140.6	3.9	0.008
T16	021B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	158.5	1.0	0.007
	022B	?*									
DCA-1295	031B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	87.4	<0.01	<0.005
	032B	0.006	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	131.8	13.3	0.019
Dynatech	041B	0.006	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	141.1	<0.01	<0.005
	042B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	149.7	0.06	0.007
Uniroyal	051B	--†	<0.001	<0.001	<0.001	0.016	0.007	--	59.0	0.54	0.020
	052B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	70.3	9.9	0.019
Aerospray 70	061B	<0.002	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	108.4	0.04	0.005
	062B	<0.002	<0.001	<0.001	<0.001	<0.005	0.002	0.0008	133.3	<0.01	0.005
AC40	071B	<0.002	<0.005	<0.001	<0.001	<0.01	<0.001	<0.0002	103.0	<0.01	<0.005
	072B	<0.002	<0.005	<0.001	<0.001	<0.01	0.001	<0.002	92.6	<0.01	<0.005
Asphaltic concrete	091B	0.004	<0.001	<0.001	<0.001	<0.005	<0.002	<0.0002	99.0	11.6	0.021
	092B	<0.002	0.004	<0.001	<0.001	<0.005	<0.002	<0.0002	122.7	0.5	0.010
Sucoat	131B	0.002	<0.005	<0.001	<0.001	CI#	0.003	<0.0002	102.0	1.4	<0.005
	132B	*<0.002§*	*<0.005*	*0.0009*	*0.015*	*<0.005*	*0.005*	*<0.0002*	*214.4*	*0.63*	*0.004*
No liner (clay)	2-400	0.004	<0.005	0.003	<0.001	<0.01	0.003	<0.0002	20.0	<0.01	<0.005
Guartec UF	081B	0.006	<0.001	0.014	0.044	<0.005	0.450	<0.0002	1197.0	1766.0	5.0
	082B	0.007	<0.001	0.017	0.040	<0.005	0.467	<0.0002	1020.0	1416.0	2.05
Cement	101B	0.005	<0.005	<0.001	0.340	0.032	0.025	<0.0002	<0.10	<0.01	0.005
	102B	*0.011*	*<0.005*	*0.0004*	*0.089*	*0.022*	*0.002*	*<0.0002*	*<0.1*	*<0.01*	*0.008*
M179	111B	<0.002	0.005	<0.001	<0.001	<0.005	0.005	<0.0002	113.3	0.06	0.029
	112B	<0.002	0.009	<0.001	<0.001	<0.005	0.003	<0.0002	109.4	1.1	0.031
Lime	121B	0.004	<0.005	<0.001	0.538	0.033	0.020	<0.0002	<0.10	0.01	0.012
	122B	0.004	<0.005	<0.001	0.205	0.025	0.013	<0.0002	<0.10	0.01	0.023
TACSS 020	141B	0.028	0.009	<0.001	<0.001	<0.005	<0.002	<0.0002	229.1	28.3	0.003
	142B	0.009	0.010	<0.001	<0.001	CI	<0.002	<0.0002	253.7	34.4	0.010
Portland cement plus lime	151B	0.002	<0.001	<0.001	0.039	0.022	0.017	0.0004	<0.10	<0.01	0.052
	152B	0.002	<0.005	<0.001	0.026	0.033	0.010	<0.0002	<0.10	<0.01	0.039
TACSS 025	161B	0.006	0.013	<0.001	<0.001	CI	<0.002	<0.0002	261.0	39.5	0.031
	162B	0.011	0.011	<0.001	<0.001	0.023	<0.002	<0.0002	299.2	50.1	<0.005
C400	171B	0.050	<0.005	<0.001	0.120	0.103	1.23	<0.0002	<0.10	<0.01	0.052
	172B	*0.139*	*<0.005*	*<0.0002*	*2.090*	*0.024*	*0.098*	*0.0004*	*<0.1*	*<0.01*	*0.042*
CST	181B	0.004	<0.005	<0.001	0.008	0.094	0.259	<0.0002	<0.10	<0.01	0.090
	182B	0.002	<0.005	<0.001	0.029	0.082	0.200	<0.0002	<0.10	<0.01	0.120
EPA allowable values (9, 10)	--	0.05	0.011#	0.01	0.05	0.005**	0.2	0.002††	NA‡‡	0.05	0.1#

(Continued)

TABLE 11. (Continued)

Liner Material	ID No.	Lead Pb	Selenium Se	Zinc Zn	Sulfite SO_3	Sulfate SO_4	Boron B	Chloride Cl	Vanadium V	Nitrogen Nitrite NO_2, N	Nitrogen Nitrate NO_3, N
No liner (sand)	1-400	0.005	E§§	0.016	<1.0	297.0	7.4	78.0	0.018	31.6	47.5
Total Liner	011B	<0.003	<0.003	0.002	<1.0	1510.0	46.1	204.7	0.036	<0.01	<0.11
	012B	<0.003	<0.003	0.001	<1.0	1280.0	35.6	200.2	0.030	0.12	0.08
T16	021B	<0.003	<0.003	<0.001	<1.0	1230.0	32.9	229.0	0.031	<0.01	<0.05
	022B										
DCA-1295	031B	<0.003	<0.003	<0.001	<1.0	167.0	3.8	135.0	0.013	0.30	<0.05
	032B	0.005	<0.003	0.002	<1.0	1490.0	28.2	135.0	0.034	<0.01	0.26
Dynatech	041B	0.006	<0.003	<0.001	1.0	910.0	18.8	170.9	0.027	<0.01	<0.05
	042B	0.016	<0.003	0.004	1.0	1300.0	44.0	208.9	0.037	<0.01	<0.05
Uniroyal	051B	0.008	<0.003	<0.001	<1.0	--	22.5	--	0.042	--	--
	052B	<0.003	<0.003	<0.001	<1.0	1520.0	33.2	181.5	0.044	<0.01	<0.05
Aerospray 70	061B	<0.003	<0.003	0.002	1.0	530.0	13.8	95.0	0.021	<0.01	0.10
	062B	<0.003	<0.003	<0.001	<1.0	226.0	4.3	135.9	0.013	<0.01	0.12
AC40	071B	0.005	E	0.005	<1.0	342.0	2.7	73.0	0.025	0.66	1.41
	072B	0.017	E	0.005	<1.0	340.0	2.1	50.0	0.019	<0.01	0.31
Asphaltic concrete	091B	<0.003	<0.003	0.004	1.0	1500.0	37.8	227.9	0.045	<0.01	0.30
	092B	0.005	0.005	0.006	1.0	494.0	8.8	164.6	0.024	0.02	4.82
Sucoat	131B	<0.003	E	0.009	<1.0	872.0	0.8	68.0	0.027	<0.01	<0.05
	132B	*0.004*	*0.006*	*0.022*	*<1.0*	*2070.0*	*4.1*	*91.0*	*0.039*	*3.15*	*4.7*
No liner (clay)	2-400	0.005	E	0.026	<1.0	36.0	0.6	79.0	0.005	<0.01	<0.05
Guartec UF	081B	0.048	<0.003	2.79	10.1	100.0	28.0	685.7	0.500	CI	CI
	082B	0.030	<0.003	2.26	12.0	92.0	37.5	597.8	0.565	CI	CI
Cement	101B	<0.003	E	<0.001	<1.0	117.0	0.3	151.0	0.013	0.05	<0.05
	102B	*0.004*	*0.017*	*0.003*	*7.2*	*1030.0*	*4.8*	*167.0*	*0.031*	*0.08*	*<0.05*
M179	111B	0.009	<0.003	0.005	<1.0	1750.0	21.6	423.0	0.042	<0.01	0.11
	112B	0.009	<0.003	0.007	1.0	1560.0	10.7	580.2	0.039	<0.01	0.12
Lime	121B	0.007	E	0.001	1.0	194.0	0.3	150.0	<0.005	0.07	<0.05
	122B	0.006	E	<0.001	1.5	833.0	0.3	153.0	0.018	0.04	<0.05
TACSS 020	141B	<0.003	<0.003	0.001	1.0	340.0	6.1	622.4	0.041	<0.01	0.26
	142B	<0.003	<0.003	0.001	38.4	570.0	18.6	736.4	0.048	<0.01	0.38
Portland cement plus lime	151B	<0.003	<0.003	0.004	<1.0	4.0	0.4	19.4	0.006	0.15	<0.05
	152B	0.022	<0.003	0.002	5.0	20.0	0.4	29.1	0.006	0.03	<0.05
TACSS 025	161B	<0.003	<0.003	0.001	22.8	570.0	25.4	379.9	0.056	<0.01	<0.05
	162B	0.014	0.004	0.002	140.6	1290.0	45.4	643.5	0.090	<0.01	0.97
C400	171B	0.042	0.005	0.021	365.0	4560.0	1.4	462.1	0.271	<0.01	<0.05
	172B	*0.068*	*0.140*	*0.004*	*14.0*	*3939.0*	*5.4*	*460.0*	*0.363*	*0.14*	*<0.05*
CST	181B	0.045	<0.003	0.003	10.0	29.0	0.3	77.7	0.007	0.57	0.15
	182B	0.007	<0.003	0.003	25.0	21.0	0.3	71.9	0.008	0.37	0.27
EPA allowable values (9, 10)	--	0.05	0.01	5.0††	NA	250.0	0.75##	250.0††	NA	10.0	10.0

* ? = Insufficient leakage to date (<<32 oz).
† -- = Insufficient sample to analyze for all parameters.
‡ CI = Chemical insufficient.
§ Entries types in script are 24-month data.
# Freshwater aquatic life criteria.
** Freshwater and marine organisms criteria.
†† Secondary standards proposed for drinking water criteria (EPA).
‡‡ NA = Not available.
§§ E = Equipment being repaired.
Irrigation criteria.

TABLE 12. SPECIFIC CONDUCTANCE AND pH VALUES FOR FIRST 32 OZ OF SLUDGE A AND B LEACHATE FROM LINED AND UNLINED TEST CELLS

Liner Material	ID No.	Sludge A Specific Conductance* (μmhos/cm)	Sludge A pH†	Sludge B Specific Conductance (μmhos/cm)	Sludge B pH
No liner (sand)	—	1423	7.33	1642	8.18
Total Liner	011‡			3156	7.43
	012	2525	7.18	2928	7.81
T16	021	2729	7.16	2729	7.60
	022	1683	7.86	§	§
DCA-1295	031	2104	7.51	1263	7.96
	032	2020	7.70	2805	7.36
Dynatech	041	2623	7.50	2195	7.41
	042	2885	7.40	2805	7.60
Uniroyal	051	1683	7.99	**	7.91
	052	2805	7.46	3015	5.43
Aerospray 70	061	1712	7.80	1507	7.99
	062	§	§	1629	7.67
AC40	071	1578	7.30	3061	7.36
	072	§	§	1683	7.76
Asphaltic	091	3367	7.48	3206	7.30
concrete	092	§	§	2104	7.50
Sucoat	131	1741	7.64	1870	7.72
	132	1507	7.83	§	§
No liner (clay)	--	721	7.42	652	7.39
Guartec UF	081	NA††	NA	NA	NA
	082	NA	NA	NA	NA
Cement	101	3150	11.65	4810	7.85
	102	1485	11.13	4698	8.16
M179	111	4391	7.83	4810	7.85
	112	3885	7.69	4698	8.16
Lime	121	2730	11.71	3156	11.85
	122	2149	11.29	3156	11.73
TACSS 020	141	3675	7.22	3741	7.40
	142	2928	7.50	4040	7.28
Portland cement	151	2525	11.50	1443	9.08
plus lime	152	1804	10.41	1942	7.92
TACSS 025	161	3483	7.28	3258	7.66
	162	2886	7.27	4122	7.19
C400	171	**	**	19423	12.00
	172	**	**	**	**
CST	181	4810	11.20	5050	9.35
	182	3607	9.57	4591	9.30

* California Consumer-Acceptance Limits (1972) recommend a specific conductance of 800 with an upper limit of 1600 and maximum short term of 2400 μmhos/cm.

† EPA water-quality criteria for marine aquatic life require the pH range to be from 6.5 to 8.5.

‡ The A (e.g., 011A) values are in the column headed Sludge A and the B (e.g., 011B) are in the column headed Sludge B.

§ Insufficient leakage for test.

** Insufficient sample.

†† NA = Not available.

is not directly determinable, and it varied with the nature of the liner and the application rate of liner material.

During the testing of the liner materials, the simulated head (compressed air) forced the liquid or liquor associated with the FGD sludges through the liner and into the soil. Two different FGD sludges were used in this testing program, but the liquids associated with them were quite close in composition. The liquid was alkaline (pH 9 to 10.3) and saturated with gypsum and calcium carbonate. The chemical compositions of these liquid sludges and of the first leachates that passed through sand and clay soils only (without liners) are given side by side for comparison in Table 13. Chemical values for all other first leachates (those that passed through a liner) are presented in Tables 10 and 11.

Silicone Seal

When the sludge was removed from the cells, the silicone bond with the various liners and with the cell was not adhering adequately and was a possible source of leaking. If the silicone bonds were leaking, the permeability values would be influenced and possibly invalidated; however, other data would be valid and useful, the testing and aging during the past year would not be completely lost, and the test would continue for the second year. Efforts were made to determine where the silicone bonds were leaking and the quantity leaked (discussed in Section 7). When these efforts proved fruitless, steps were taken to normalize or weigh the permeability data for further use. These steps also proved hopeless so most permeability values were suspect and not reported, but the 2-year test program, at this time well under way into the second year, was continued.

TWENTY-FOUR MONTH DATA

At the end of 24 months, the remaining 32 test cells were depressurized, as they were at the end of the 12-month period, and disassembled for testing (tests on Guartec UF and M179 materials were discontinued at the end of 12 months). The seven admix liner materials, the five spray-on and two membrane liner materials, and the asphalt liner materials (one an admix and one a spray-on) were handled and treated for testing in the same manner used for liners inspected after 12 months.

Physical Tests

All physical test data and observations on each liner after 24 months are presented in Tables 14 and 15. The notes and remarks that apply to leakage (which affects permeability) indicate that in approximately 60 percent of the tests, the bond between the silicone, liner, and/or the test cell allowed liquid sludge to pass through, affecting the calculated permeability values. Because of this leakage and the inability to weigh and normalize permeability data, only zero permeability values and permeability values for liners that disintegrated or were obviously attacked by chemicals are reported.

TABLE 13. CHEMICAL ANALYSES OF LIQUID SLUDGE AND OF FIRST LEACHATES THROUGH SAND AND CLAY SOILS (mg/ℓ)

Parameter	Sludge A			Sludge B		
	As Received (Liquid)	Sand* (2-100)	Clay† (1-100)	As Received (Liquid)	Sand‡ (1-400)	Clay§ (2-400)
Arsenic	0.003	0.003	0.002	0.003	0.004	0.004
Beryllium	0.005	0.005	0.005	<0.005	0.005	0.005
Cadmium	0.001	0.002	0.002	<0.001	0.003	0.003
Chromium	0.001	0.001	0.001	<0.001	0.001	0.001
Cyanide	0.012	0.029	0.01	0.018	0.034	0.01
Copper	0.009	0.013	0.001	0.010	0.003	0.003
Mercury	0.002	0.0002	0.0002	0.002	0.002	0.002
Magnesium	10.1	65.1	22.2	13.8	74.1	20.0
Manganese	2.3	0.01	0.35	0.95	0.01	0.01
Nickel	0.003	0.005	0.005	0.003	0.005	0.005
Lead	<0.003	0.006	0.010	0.003	0.005	0.005
Selenium	<0.003	E**	E	0.007	E	E
Zinc	0.002	0.020	0.020	0.002	0.016	0.026
Sulfite	<1.0	1.0	1.0	<1.0	1.0	1.0
Sulfate	1281.0	241.0	42.0	2100.0	297.0	36.0
Boron	14.0	14.7	1.1	71.2	7.4	0.6
Chloride	675.0	83.0	95.0	670.0	78.0	79.0
Vanadium	E	0.021	0.005	E	0.018	0.005
Nitrite, nitrogen	0.01	14.3	0.01	<0.01	31.6	0.001
Nitrate, nitrogen	<0.5	75.6	0.33	0.51	47.5	0.05

* Smaller concentration of chemicals filtered through the clay than through the sand in all cases except manganese, lead, and chloride. With lead (0.010 vs <0.003), cadmium, magnesium, and zinc, the concentration was larger than those present in the initial liquid sludge.

† Smaller concentration of chemicals filtered through the clay than through the sand in all cases except zinc and chloride. With zinc (0.026 vs 0.002), cadmium, magnesium, and lead, the concentration was larger than those present in the initial liquid sludge.

‡ A concentration of chemicals greater than that in the original liquid sludge filtered through the sand in the following cases: cyanide, magnesium, lead, zinc, nitrogen nitrite, and nitrogen nitrate. Approximately 2 times more lead filtered through the sand, 1000 times as much nitrogen nitrite and 150 times as much nitrogen nitrate. The latter two cases indicate that the nitrogen in the solid sludge was combining with oxygen.

§ A concentration of chemicals greater than that in the original liquid sludge filtered through the sand in the following cases: cyanide, magnesium, lead, nitrogen nitrite, and nitrogen nitrate. Approximately 2 times more cyanide and lead filtered through the sand, 5 times as much magnesium, 10 times as much zinc, 3000 times as much nitrogen nitrite, and 100 times as much nitrogen nitrate. The latter two cases indicate that the nitrogen in the solid was combining with oxygen.

** E = Equipment being repaired.

TABLE 14. PHYSICAL TEST RESULTS FOR ADMIX LINERS AFTER 24 MONTHS

ID No.	Liner Material	Application Rate (%)	Water Content (%)	Dry Density (pcf)	Sample Height Diameter H/D	Axial Strain	Unconfined Compression (psi)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
102A	Portland cement	10	24.0	98.6	2.04	0.01	1282.9		The silicone sealant had lost about 95 percent of its bond with both the cylinder and the liner.
			22.2	101.3	2.16	0.01	1882.5		
			22.2	101.9	2.02	0.01	1947.2		
102B			21.4	103.4	2.00	0.01	1971.7		Approximately 20 $in.^2$ of the surface of the liner was soft and friable on both liners A and B. Actual source of leakage* could not be determined.
			21.9	102.2	1.98	0.01	1723.1		
			20.9	103.5	2.00	0.01	2090.8		
122A	Lime	10	20.6	130.6	1.97	0.01	1477.0		A thin layer of sludge solids had bound so firmly to the stabilized soil surface that the 1/8-in.-deep patches (one 4 in. in diameter and one 1-1/2 by 2-1/2 in.) were pulled away when the sludge was removed. Slight leakage could be observed around the areas where the silicone sealant had lost its bond.
			21.6	102.3	1.98	0.01	1459.5		
			21.7	102.2	1.99	0.01	1438.1		
122B			21.1	104.6	1.95	0.01	1600.6		
			21.3	104.2	1.96	0.01	1633.8		
			22.6	101.7	1.98	0.01	1212.6		
			21.7	103.7	1.94	0.01	1555.1		
142A	TACSS 020	6	17.4	105.2	1.89	0.07	137.6		The cylinder-silicone-sealant bond was good. The silicone-sealant-liner bond was poor. The point of leakage could not be determined. The sludge solids penetrated the liner surface approximately 3/8 in. deep. The liner surface appeared good and felt hard to the touch but was very brittle and crumbly.
			16.7	105.6	1.90	0.08	147.3		
			16.8	106.7	1.73	0.07	130.3		
142B			17.6	105.8	1.95	0.08	111.7		
			17.3	105.1	1.94	0.07	112.2		
152A	Portland cement plus lime	4/6	21.3	103.2	1.95	0.01	1441.2		A 1/8- to 1/4-in. layer of sludge solids had bonded to the liner surface. Attempts to remove the sludge caused the liner surface to "dish." The remaining sludge was left on the liner. Leakage was probably between the silicone-liner interface.
			20.7	104.3	1.94	0.01	1234.4		
			21.8	102.0	1.96	0.01	1491.0		
152B			20.1	106.3	1.99	0.01	1599.5		
			20.2	106.3	1.95	0.01	1617.5		
			20.5	105.8	1.97	0.01	1567.3		

(Continued)

TABLE 14. (Continued)

ID No.	Liner Material	Application Rate (%)	Water Content (%)	Dry Density (pcf)	Sample Height Diameter H/D	Axial Strain	Unconfined Compression (psi)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
162A	TACSS 025	6	16.9	107.3	1.61	--	--		Samples fell apart while being removed from cylinder H/D < 2.00, remaining pieces too short for UC testing. The silicone sealant-cylinder-liner bond was good. Sludge penetrated the liner surface approximately 15/16 in.
			17.0	106.8	1.36	--	--		
162B†		--	--	--	--	--	--		
			--	--	--	--	--		
172A	C400	15	19.6	106.3	1.95	0.01	1662.9	0.002	Bond between the cylinder wall and the silicone sealant was very good. Bond between the silicone sealant and the liner was loose in several places and was probably the source of leakage* although this could not be documented. Some penetration (approximately 1/8 in.) over approximately 9 $in.^2$ area. Underneath the penetration area, the liner was very hard.
			19.6	106.9	1.99	0.01	1561.6		
			20.3	105.7	1.98	0.01	1531.2		
172B			20.1	106.2	1.99	0.01	1436.2	0.001	
			19.6	107.6	1.98	0.01	1653.2		
182A	CST	15	21.0	104.6	1.98	0.01	1561.6	0.002	The silicone-cylinder-liner bond was loose in several places. Some sludge solids beneath the sealant. Liner was soft and crumbly to a depth of approximately 1/4 in., but below this depth the liner was very hard.
			20.7	105.9	1.97	0.01	1730.5		
			21.5	103.7	1.97	0.01	1707.4		
			20.8	104.4	1.99	0.01	1995.5		
182B			19.6	106.7	1.99	0.01	1929.8	0.002	
			20.5	105.1	2.00	0.01	1857.8		
			19.6	106.5	1.96	0.01	2167.9		

		Asphalt Content	Penetration (0.1 mm)	Viscosity (poises)	Permeability ($cm/sec \times 10^{-6}$)	
092A	Asphalt concrete	9.9	72	2280	0.000	The silicone-cylinder-liner bond was very good. This liner did not leak.
092B		9.7	61	2675	0.475	The silicone-cylinder-liner bond was very good; leakage occurred through the liner itself.*

* Leakage, where mentioned, was detected by locating the source of air bubbles observed due to 2-psi back pressure through the drain port after approximately 1 in. of water was placed over the liner.

† Could not core a good specimen for test.

TABLE 15. PHYSICAL TEST RESULTS FOR SPRAY-ON AND MEMBRANE LINERS AFTER 24 MONTHS

ID No.	Liner Material	Thickness (in.)	Weight (g)	Density (pcf)	Application Rate	Elongation (%)	Breaking Strength (lb)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
012A	Total Liner	0.018	8.79	77.5	As received	433	124		This liner material was still soft and pliable and appeared to be in good condition. Leakage* was probably due to the silicone-liner bond being loose in several places, although this could not be verified (see note below for verification procedure).
		0.022	9.89	71.4		652	178		
012B		0.023	12.48	74.1		576	167		
		0.023	12.21	73.6		576	160		
022A	T16	0.023	11.95	82.5	As received	60	430		The sealant-cylinder bond was poor as evidenced by slight bubbling (see note below).
		0.023	12.00	82.8		65	490		
022B		0.028	15.90	90.1		29	368	0.000	The sealant-cylinder-liner bond was good. Some crust buildup on liner surface. This liner did not leak.
		0.035	15.90	72.1		30	392		
032A	DCA-1295	0.140	90.91	103.1	75 gsy	47	32	0.010	The sealant-cylinder-liner bond was good. Liner was badly discolored. The liner was easily torn during attempts to remove it from the test cell and also while trying to remove the sealant from the liner. The worst decomposition appeared to be on the bottom side of the liner.
		0.140	87.30	99.0		29	34		
032B		0.051	22.46	69.9		1	10	0.314	
		0.030	13.55	71.7		2	29		
042A	Dynatech	0.109	44.88	65.3	75 gsy	508	122		The sealant-cylinder-liner bond was good. The source of leakage could not be determined. Liner was discolored.
		0.109	49.67	72.2		492	128		
042B		0.077	44.48	91.7		502	118		The sealant-cylinder bond was loose in one spot indicated by bubbling (see note). Liner was discolored.
		0.111	31.45	45.0		479	75		
052A	Uniroyal	0.080	31.87	63.2	75 gsy	623	70	0.022	The sealant-cylinder-liner bond was good. Souce of leakage could not be determined. The liner was discolored.
		0.080	31.92	63.3		611	70		
052B		0.091	39.34	68.6		628	105		The sealant-liner bond was poor. The liner was discolored. The source of leakage could not be determined.
		0.071	28.40	63.5		597	65		

* Leakage where mentioned was detected by locating the source of air bubbles observed due to 2 psi back pressure through the drain port after approximately 1 in. of water was placed over the liner.

(Continued)

TABLE 15. (Continued)

ID No.	Liner Material	Thickness (in.)	Weight (g)	Density (pcf)	Application Rate	Elongation (%)	Breaking Strength (lb)	Permeability (10^{-6} cm/sec)	Remarks
062A	Aerospray 70	0.110	70.20	101.3	75 gay	191	62	0.000	The sealant-cylinder-liner bond was good for both test cells. Both liners were badly discolored and apparently underwent chemical attack (decomposing) from beneath (the liner/soil interface).
		0.125	73.45	93.3		252	64		
062B		0.140	83.45	94.7		174	50	0.004	
		0.125	71.20	90.4		222	52		
132A	Sucoat	0.455	362.19	126.4	As received	--	120	0.004	Liner cracked in spider web pattern into six pieces. Sealant-liner bond poor and probable source of leakage, although this could not be documented (see note).
132B		0.464	372.00	127.2		--	250	0.050	
		0.520	379.04	118.4		--	192		

ID No.	Liner Material	Asphalt Content	Penetration (0.1 mm)	Viscosity (poises)	Permeability (10^{-6} cm/sec)	Remarks
072A	AC40	24.5	45	9039	0.034	The sealant-cylinder-liner bond was good.
072B		23.3	45	9048	0.065	Leakage occurred through the liner itself near the center.

Admix Liners--

The admix liner materials were tested for UC values. Figure 16a shows that sludge settled in a random crack pattern on the lime liner in the test cell. When the sludge was removed from the lime liner surface, patches of soft crumbly soil were removed with the sludge (Figure 16b). The cored lime liner material is shown in Figure 17 prepared for the UC test. The sludge pattern after settling on the Portland cement liner in the test cell is shown in Figure 18a, and the C400 liner in the test cell after the sludge was removed from the surface is shown in Figure 18b. Figure 19 shows typical cored liner specimens after failure in UC tests.

Spray-on and Membrane Liners--

The spray-on and membrane liners underwent grab tests for comparable data. Figure 20 shows two of the liners in the test cell after 24 months. Note the water circle on the T16 membrane in Figure 20a. The DCA-1295 liner (Figure 20b) was discolored and apparently attacked by the sludge chemicals. When the sludge was removed from the surfaces, the Dynatech and Uniroyal liners were discolored (Figure 21), and the liner sealer was disbonded for three-fourths of the cell's circumference on the Uniroyal liner (Figure 21b). The Aerospray 70 liner was badly discolored (Figure 22) and appeared to be thin in spots. Grab test specimens, 4 by 6 in., were cut out of AC40, but the specimens were cracked (Figure 23) and could not be tested in this manner. The asphalt liner was extracted and tested for penetration and viscosity. Figure 24 shows the disc liners of Dynatech and Sucoat removed from the test cell and cut into specimens for grab tests.

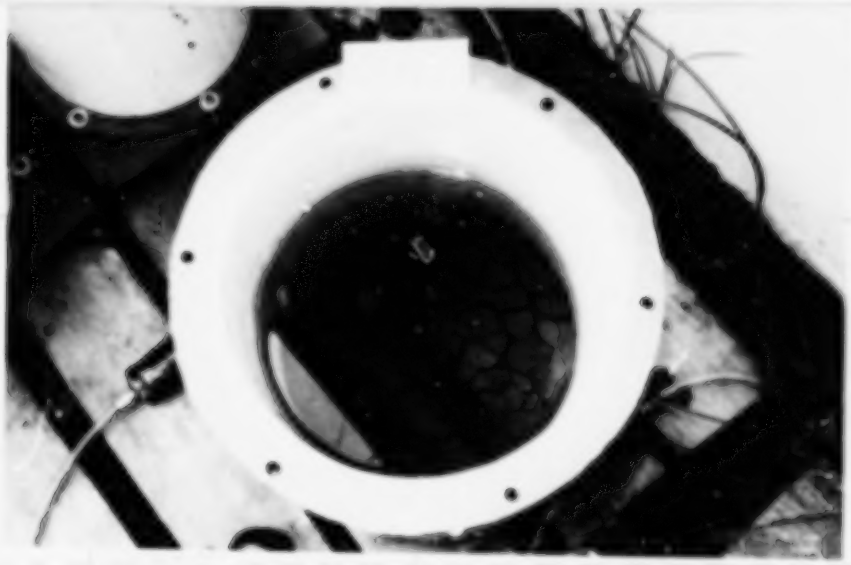
Representative 24-month physical test data on the liners are shown in Tables 16 and 17, along with comparable data for each liner at zero time (beginning of test) and at 12 months.

Permeability

Only permeability data on liners that permitted no leachate or liners that were obviously attacked by the chemical sludges which caused the liner to pass leachate are reported. Where no leakage occurred, it was obvious that the silicone seal was effective. However, the permeability values on liners that were attacked chemically would probably be influenced by the silicone seal that leaked.

Chemical

After 24 months, leachate liquid for chemical analysis was obtained from only five test liners. These are AC40, C400 (Sludge A), Sucoat, Portland cement, and C400 (Sludge B). Tables 10 and 11 present these data (in script typing) along with the 12-month chemical data. No leachate was obtained from the test liners Aerospray 70, asphaltic concrete, C400, or T16. Other liner cells were either discontinued (Guartec UF and M179), or the quantity of leachate after 12 months was not sufficient to analyze, and/or all liquid sludge had leached through the cell soil during the first 12 months.

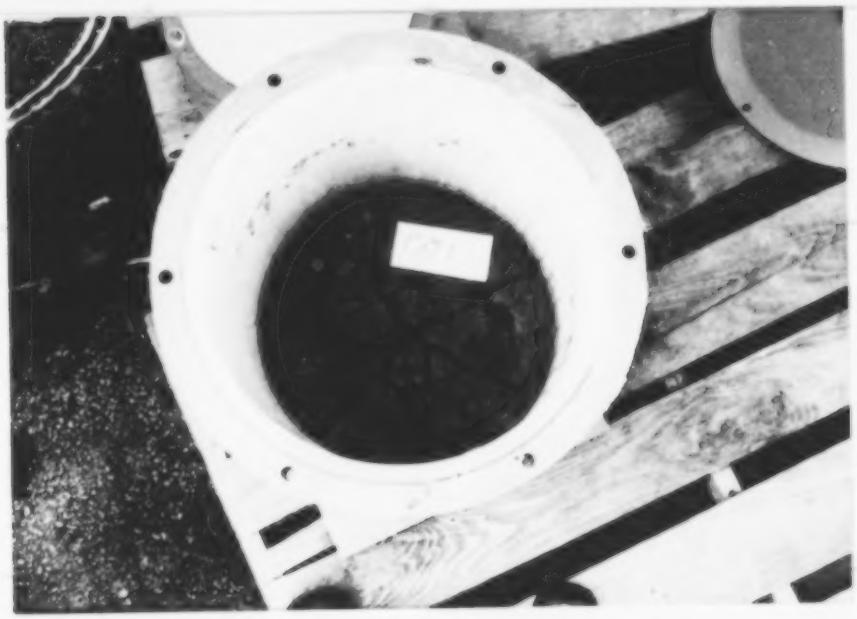


a. Crack sludge pattern after 24 months.

b. Top of liner after sludge removed.

Figure 16. Lime liner in test cell.

Figure 17. Cored lime liner prepared for the UC test.

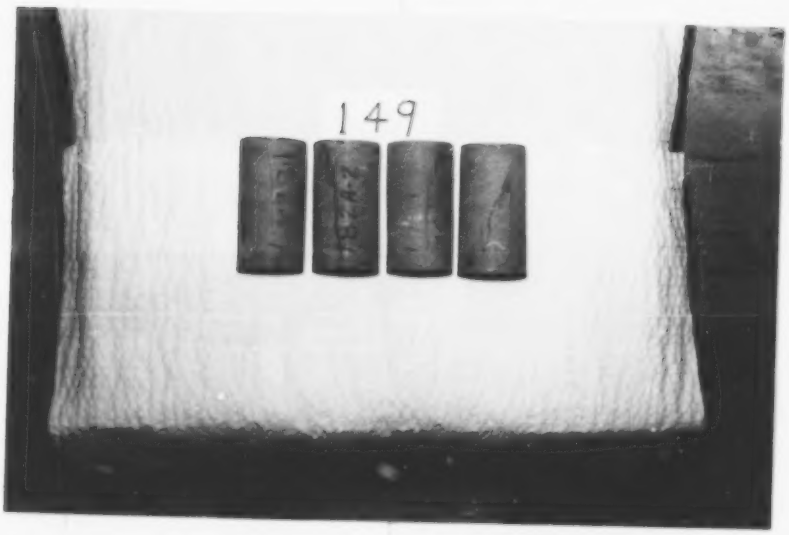


a. Portland cement liner showing pattern of cracked sludge settled on surface.

b. C400 surface after sludge removed.

Figure 18. Test cells with liners in place after 24 months.

a. Cement and lime showing sheared liner.



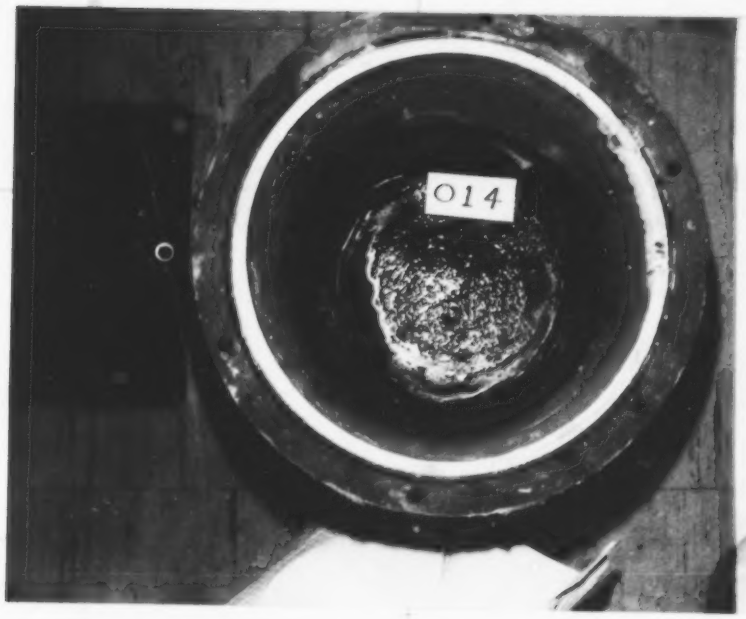
b. CST showing sheared liner.

Figure 19. Typical cored liner specimens after failure in the UC test.

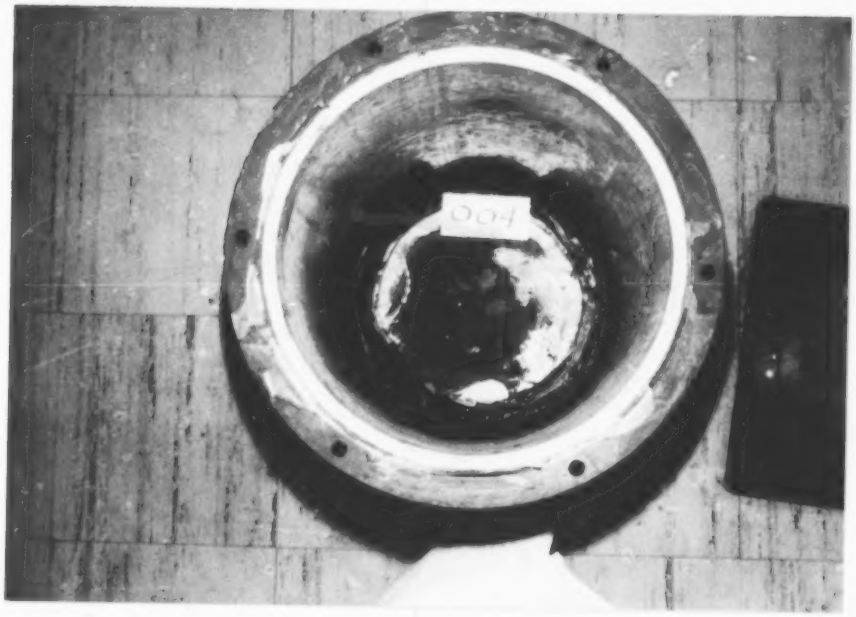
a. T16 liner showing water circle.

b. DCA-1295 liner discolored by sludge.

Figure 20. Spray-on and membrane liners in test cells after 24 months (sludge removed from top surface).



a. Dynatech liner.



b. Uniroyal liner disbonded from the sealant for three-fourths of the cell's circumference.

Figure 21. Discolored (Dynatech and Uniroyal) liners in test cells after sludge removal.

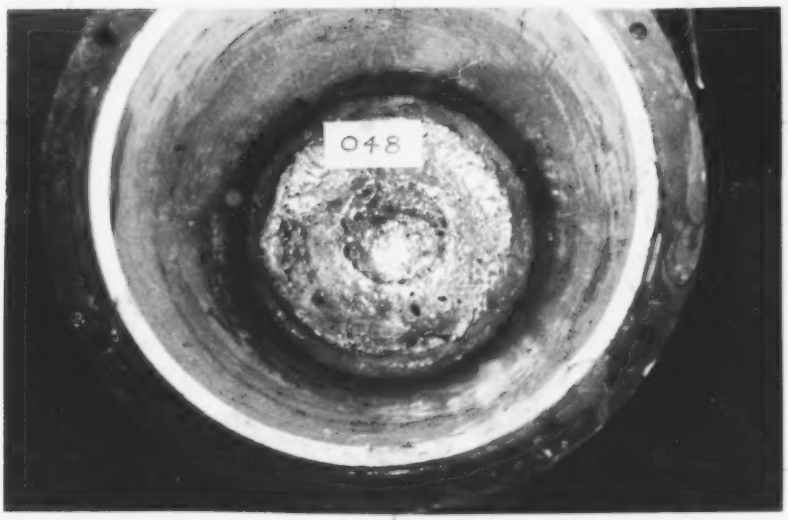


Figure 22. Aerospray 70 liner, discolored and thinned in small areas.

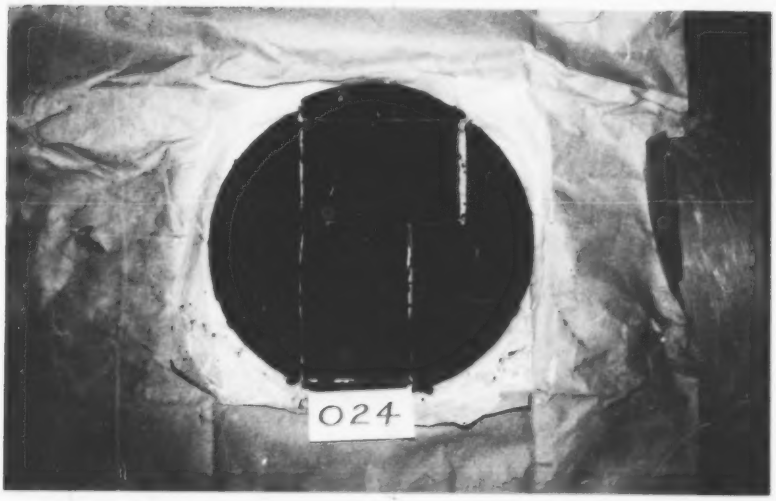
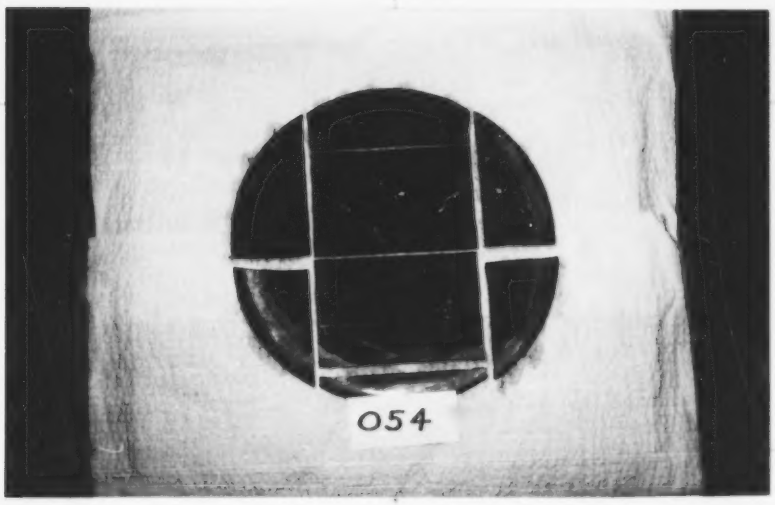
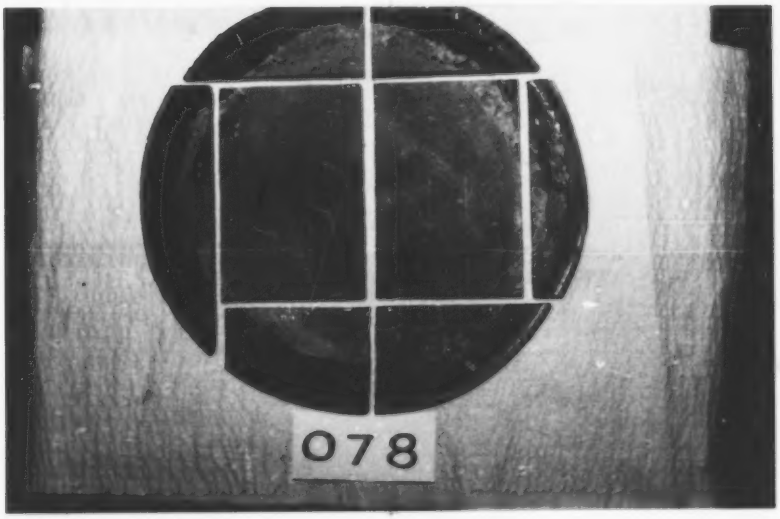


Figure 23. AC40 liner cut for grab test (note cracks).



a. Dynatech liner.



b. Sucoat liner.

Figure 24. Disc liners of Dynatech and Sucoat cleaned of sludge and removed from test cell (note the two 4- by 6-in. specimens cut in each liner for grab test).

TABLE 16. REPRESENTATIVE* PHYSICAL TEST DATA FOR ADMIX LINERS AT ZERO-TIME, 12, AND 24 MONTHS

ID No.	Liner Material	Application Rate (%)	Water Content (%)	Dry Density (lb/ft^3)	Sample Height / Diameter H/D	Axial Strain ($\Delta H/H$, %)	Unconfined Compression ($lb/in.^2$)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
000A	Clayey silt	NA†	16.6	103.5	2.051	3.1	38.4	7	Untreated soil. Tested following seven days of humid cure.
000B			16.6	103.5	2.051	3.1	38.4	1	
100	Portland cement	10	16.6	102.8	2.155	1.0	663		
101A			21.0	103.0	2.094	1.0	1779		Very hard to core samples.
101B			20.3	103.6	2.111	1.0	1893		
102A			22.8	100.6	2.070	1.0	1704		Approximately 20 $in.^2$ of surface of liner was soft and friable on liners A and B. Silicone sealant lost 95 percent bond.
102B			21.4	103.0	2.000	1.0	1928		
120	Lime	10	17.3	101.0	2.153	1.0	242		
121A			20.1	100.8	2.073	1.0	1294		Very hard to core samples.
121B			22.3	101.7	2.073	1.0	1200		
122A			21.3	102.7	1.98	1.0	1458		Sludge bonded to liner and small amount of liner was removed with sludge. Leakage occurred at disbonded sealant.
122B			21.7	103.5	1.96	1.0	1500		
140	TACSS 020	6	16.2	106.3	2.154	6.3	179		
141A			16.7	105.9	2.153	6.6	148		Very hard to core samples.
141B			16.5	105.9	2.159	6.3	162		
142A			17.0	105.8	1.84	7.0	138		Sludge penetrated liner 3/8 in.
142B			17.5	105.5	1.94	7.0	112		Liner surface was hard and crumbly.
150	Portland cement	4/6	16.1	104.1	2.172	1.0	503		
151A	plus lime		20.4	103.7	2.118	1.0	1297		2-psi back pressure failed to produce any
151B			20.1	104.4	2.063	1.0	1496		bubbles that would indicate leaks.
152A			21.3	103.2	1.95	1.0	1389		Leakage was probably between silicone-liner interface.
152B			20.3	106.1	1.97	1.0	1595		Sludge bonded to liner and difficult to remove.
160	TACSS 025	6	16.4	104.6	2.173	5.0	164		
161A			17.1	108.8	2.157	7.0	147		
161B			18.3	104.0	2.160	7.0	144		
162A			17.0	107.0	1.48	NA	NA		Could not obtain a desirable core for testing. Sludge penetrated liner 15/16 in.
162B			NA	NA	NA	NA	NA		
170	C400	15	15.9	105.4	2.111	1.0	721		
171A			20.3	104.2	2.106	1.0	1510		Very hard to core samples.
171B			19.8	105.6	2.171	1.0	1294	0.003	
172A			19.8	106.3	1.97	1.0	1585	0.002	Some sludge penetration (approx. 1/8 in.)
172B			19.9	106.9	1.98	1.0	1545	0.001	over an approx. 9-$in.^2$ area.
180	CST	15	14.4	105.2	1.792	1.0	1160		
181A			19.0	106.2	2.118	1.0	1792	0.011	Very hard to core samples.
181B			19.9	105.3	1.953	1.0	2091	0.004	
182A			21.0	104.7	1.98	1.0	1749	0.002	Liner was soft and crumbly to a depth of
182B			19.9	106.1	1.98	1.0	1985	0.002	approx. 1/4 in. but below this depth the liner was very hard.

		Asphalt Content (%)	Penetration (0.1 mm)	Viscosity (poises)	Permeability ($cm/sec \times 10^{-6}$)	
090	Asphaltic concrete	10.4	60	2959		
091A	11% asphalt	11.2	68	3749		Silicone seal questionable.
091B	1/2-in. aggregate	10.3	62	2945		Silicone seal poor.
092A		9.9	72	2280	0.00	No leakage passed. Silicone bond was good.
092B		9.7	61	2675		Minor leakage occurred through liner.

* Values represent averages of results for several tests.
† NA = Not available.

TABLE 17. REPRESENTATIVE* PHYSICAL TEST DATA FOR SPRAY-ON AND MEMBRANE LINERS FOR ZERO TIME, 12, AND 24 MONTHS

ID No.	Liner Material	Thickness (in.)	Weight (g)	Density (lb/ft^3)	Application Rate (lb/yd^2)	Apparent Elongation (%)	Breaking Strength (lb)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
000A	Silty sand	NA†	NA	111.0	NA	NA	NA	49	Untreated soil.
000B		NA	NA	111.0	NA	NA	NA	47	
010	Total Liner	0.023	7.77	54.58	0.92	136	544		
011A		0.022	9.10	63.66	1.07	573	158		Leakage apparently developed between liner and sealant along 1/2-in. strip.
011B		0.025	9.80	63.98	1.15	464	134		
012A		0.020	9.34	74.45	‡	543	151		
012B		0.023	12.35	73.90	‡	576	164		
020	T16	0.018	8.95	75.75	1.04	26	482		
021A		0.018	15.38	88.77	1.77	25	345		Leakage developed in two places between liner and sealant. Total length of leaking strip was approximately 1/2 in.
021B		0.017	16.62	94.35	1.95	28	374		
022A		0.023	15.90	82.65	‡	62	460		
022B		0.031	15.90	81.13	‡	29	380	0.0	Sealant bond was good. No leaks.
030	DCA-1295	0.219	112.44	81.42	13.42	172	127		
031A		0.177	65.14	88.95	7.76	95	47	0.368	The liner was discolored and apparently disolved from chemical attack. Two small holes at liner edge, liner very thin elsewhere. Liner decomposed on bottom surface.
031B		0.103	34.08	55.40	4.06	52	22	0.066	
032A		0.140	89.1	101.05	‡	38	33	0.010	
032B		0.041	18.01	70.80	‡	2	20	0.314	
040	Dynatech	0.093	29.98	55.50	3.87	486	128		Liner and sealer leaked. Liner was discolored.
041A		0.100	40.79	64.23	4.79	496	82		
041B		0.113	41.99	58.72	4.95	521	118		Liner was discolored.
042A		0.109	47.28	68.74	‡	500	125		Sealant disbonded and leaked.
042B		0.094	38.17	68.35	‡	491	97		
050	Uniroyal	0.111	35.39	53.45	4.43	615	122		
051A		0.088	34.31	60.83	4.04	584	68	0.0	Liner and sealer separated.
051B		0.086	32.93	60.26	3.89	607	70		
052A		0.080	31.90	62.25	‡	617	70	0.022	Sealant did not leak. Liner discolored.
052B		0.081	33.87	66.06	‡	612	85		Sealant bond was poor. Liner discolored.
060	Aerospray 70	0.158	80.77	82.27	9.74	235	106		
061A		0.071	38.61	83.11	4.36	174	37	0.034	Liner badly discolored and very thin in spots apparently due to chemical attack.
061B		0.096	96.00	165.88	11.34	55	34	0.040	
062A		0.118	71.83	97.29	‡	222	63	0.0	Sealant bond good. Liners discolored and decomposed underneath sludge.
062B		0.133	77.37	92.57	‡	198	51	0.004	
130	Sucoat	NA	NA	NA	NA	NA	NA	NA	
131A		0.420	320.83	120.32	37.88	6	225	0.085	Four discs 3/8 in. thick received from manufacturer. All four used in test cells.
131B		LINER SHATTERED WHEN TEST CELL RUPTURED UNDER PRESSURE						0.064§	
132A		0.455	362.19	118.42	AS RECEIVED	**	192	0.004	Sealant bond poor on both specimens and probably leaked.
132B		0.492	375.52	126.78		**	185	0.050	

ID No.	Liner Material	Asphalt Content (%)	Penetration (0.1 mm)	Viscosity (poises)	Permeability ($cm/sec \times 10^{-6}$)	Remarks
070	AC40	NA	49	8,237	--	
071A		19.5	42	14,752	0.067	Center of liner leaked. No apparent leaks around sealant. Liner ruined when removed.
071B		27.6	42	13,644	0.105	
072A		24.5	45	9,039	0.034	Sealant bond good. Leak occurred at center of liner.
072B		23.3	45	9,048	0.065	

* Values represent averages of results for several tests.

† NA = Not available.

‡ Application rate approximately the same as A and B immediately above. For example, 012A and 012B are approximately the same as 011A and 011B; 022A and 022B are approximately the same as 021A and 021B, etc.

§ Data before cell ruptured.

** Samples slipped in jaws. Elongation not representative.

SECTION 7

ANALYSIS AND DISCUSSION OF RESULTS

The analysis and discussion is presented as physical test data dealing with UC and grab tests, and recovered asphalt. This is followed by the chemical test results, permeability values, and summary discussion of liner performance.

PHYSICAL TESTS

General

In reviews of the physical test data, the three types of liner materials should be kept in mind: the admix, spray-on, and prefabricated membrane materials. UC tests (6) were used to study the effects of 12- and 24-month inundation/pressurization of the admix liners, whereas grab tests (7) were employed to study similar effects on the spray-on and prefabricated membrane liners. Neither of these tests would yield very meaningful data for asphaltic concrete or asphalt cement liners. Tests of these two liner materials were concentrated on the asphalt cement itself. Penetration and viscosity of the asphalt cement were determined as a means of ascertaining deterioration.

Admix Liners

The results of the physical tests on the admix liners are shown in Table 16 for the zero-time, 12-, and 24-month exposures. Two of the materials, Guartec UF and M179, were obviously incompatible with either of the sludges, as a complete breakdown of the liners occurred at the end of 12 months. These two materials are considered unsatisfactory for the stated use, and further tests were discontinued. The moisture content in all samples increased slightly from zero time to 12 months and generally remained about constant at 24 months or the end of test, which indicates some initial liquid infiltration. However, the dry density remained about the same during the 2-year period, which would indicate that the soil structure had not changed. The UC strength of the Portland cement, Portland cement plus lime, C400, and CST almost doubled, whereas the lime strength increased almost six times from zero time to 12 months. At 2 years, the UC strength of the Portland cement and CST remained unchanged, the Portland cement plus lime and the C400 increased an additional 8 to 10 percent, and the lime increased an additional 20 percent. Thus the results indicated that the performances of the C400 and CST liners were similar to that of Portland cement.

Normally, at least in the case of silty clay stabilization with 10 percent lime, the UC strength has been observed to increase from 150 psi after a 7-day cure to approximately 400 psi after a 36-week cure (14). Undoubtedly, other soil types would also have similar UC versus cure-time values. However, the TACSS 020 and 025 lost 14 and 12 percent UC strengths, respectively, at the end of 12 months. At the end of 24 months, the TACSS 020 lost an additional 11 percent (total of 25 percent based on zero-time data). Data after 24 months for comparison on the TACSS 025 material was not obtained, as the specimen dissociated when cored.

The penetration of the asphaltic concrete increased approximately 10 percent at 12 months and remained constant at 24 months. However, the viscosity, based on the initial values, also increased approximately 13 percent at 12 months but decreased more than 16 percent after 24 months. A photo series (Figures 25, 26, and 27) of the asphaltic concrete liner at 12 months shows two extensive surface cracks. Covering the liner with water and applying back pressure only produced bubbles at the intersection of two cracks (Figure 26). A close-up of this liner shows the relative size of the two cracks (Figure 27).

In cases where the silicone sealant was suspected to have become disbonded from the liners and/or from the test cell wall, the above method of applying 2-psi back pressure to the resubmerged specimen was used to determine where and how much the sealant had contributed to the leachate samples. Bubbles were observed on some specimens at the disbonded sealant-liner-cell interfaces, but it was impossible to assess the quantity of leachate that could be attributed to the disbondment. The air pressure exited the larger voids and/or easiest paths, and the agitated or bubbling water tended to mask or obscure the area(s) of lesser or smaller bubbles. Also, the quantity of leakage could not be measured.

Figure 25. Asphaltic concrete liner surface showing extreme cracking.

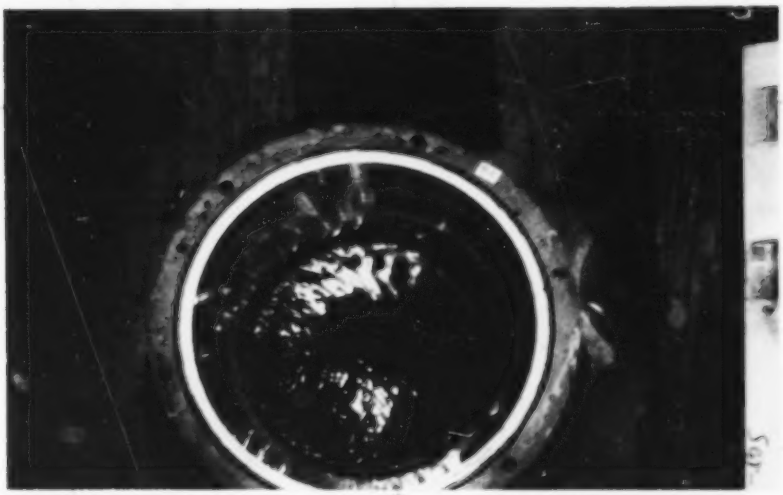


Figure 26. Asphaltic concrete liner with sludge removed, approximately 1 in. water added, and 2-psi back pressure applied (note air bubbles at 9 o'clock portion).

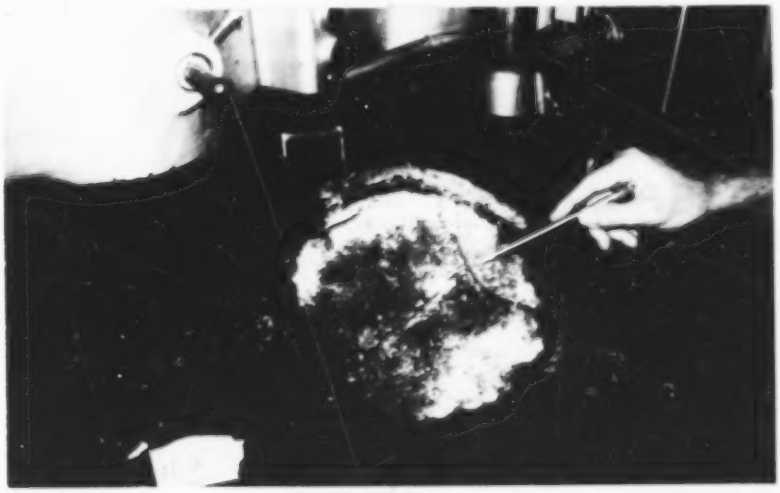


Figure 27. Close-up of cracks in asphaltic concrete liner (discolored area around periphery indicates area covered by silicone sealant).

Spray-on and Prefabricated Membrane Liners

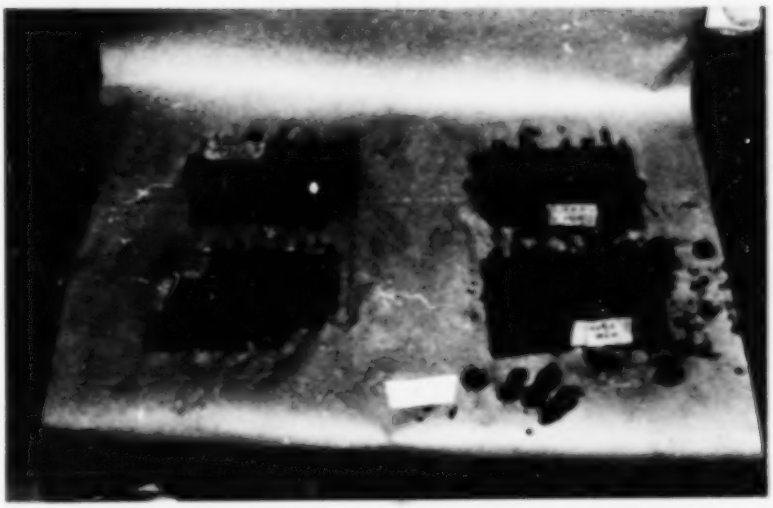
The results of the physical tests on the spray-on and membrane liners are shown in Table 17. At 12 months of exposure, the breaking strength of all the liners decreased, and the DCA-1295 continued to lose strength at 24 months. However, the strength of the Total Liner, T16, Uniroyal, Dynatech, and Sucoat increased slightly from 12 to 24 months. Figure 28 shows the DCA-1295 and Uniroyal, and Figure 29 shows the Total Liner after 12 months.

The percent of elongation values for the Total Liner material increased approximately 400 percent the first year and remained constant during the second year. The elongation values for the T16, Dynatech, and Uniroyal generally remained constant through the 2-year test period. At 24 months, the Aerospray 70 reversed its pattern from 12 months by increasing, and the DCA-1295 continued decreasing the second year. No samples or zero-time data were provided for the Sucoat specimens, and one test cell ruptured during the 12-month period. There was no evidence of chemical attack on the liner at this time or at the end of the test. At 24 months, the breaking strength of the specimens had decreased from 225 to 185 psi, or by approximately 16 percent. The elongation data were voided as the specimens slipped in the test equipment.

The AC40 test cells did not pass any liquid until after 8 months. Following teardown at 12 months, a hole was observed in one liner near the center. The liner fell apart while it was being removed from the test cell, but data on the recovered asphalt (Table 17) indicate that the penetration had decreased approximately 14 percent, whereas the viscosity had increased approximately 70 percent at 12 months. At 24 months, the penetration values had recovered approximately 7 percent; however, the viscosity decreased to within 12 percent of the original values. The asphalt changed with time, pressure, and sludges, but no trend was established.

CHEMICAL TESTS

The initial permeate water samples taken during this testing program also may have contained leachable constituents from the liners. In many cases, the effects of material lost from the liners cannot be seen because of the very concentrated liquor from the FGD sludges and normal background chemistry of the water associated with the soils. There are, however, some exceptions. For example, Guartec UF, an organic product derived from the guar bean, obviously decomposed and became putrescent. The resulting reducing conditions appear to have released manganese and magnesium or caused these elements in the soil to go into solution. The manganese and magnesium levels in the liquid from the Guartec UF test cells are an order of magnitude greater than those of other test cells. Similar conditions occurred in all sets of test cells with both Sludges A and B. Guartec UF, along with TACSS 020 and TACSS 025, also released levels of magnesium and manganese generally higher than those observed in most other samples. Locally, acidic conditions may have developed in these admixes because of decay (in the case of Guartec UF) or reactions with plasticizers (in the case of TACSS 020 or TACSS 025). No comparative 24-month chemical data were obtained on these items (Guartec UF,



a. DCA-1295.

b. Uniroyal.

Figure 28. Spray-on liner materials samples following 12 months of inundation and grab test.

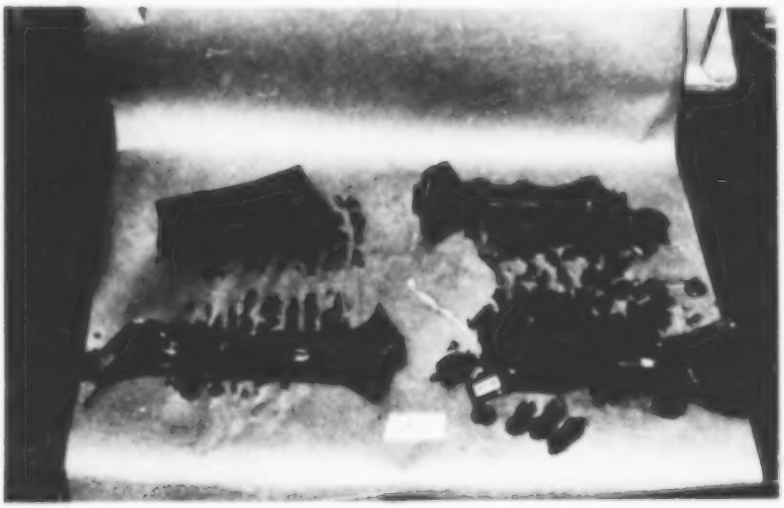
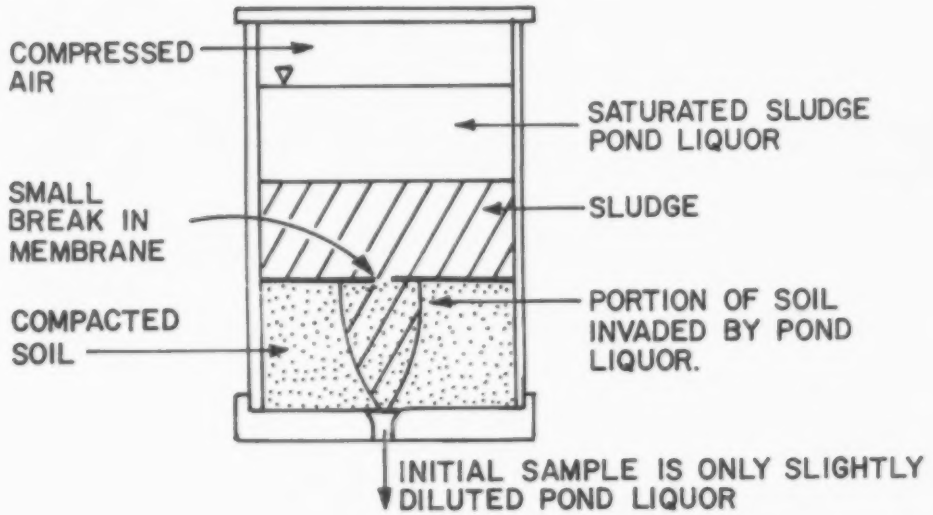


Figure 29. Total Liner material samples following 12 months of inundation and grab test.

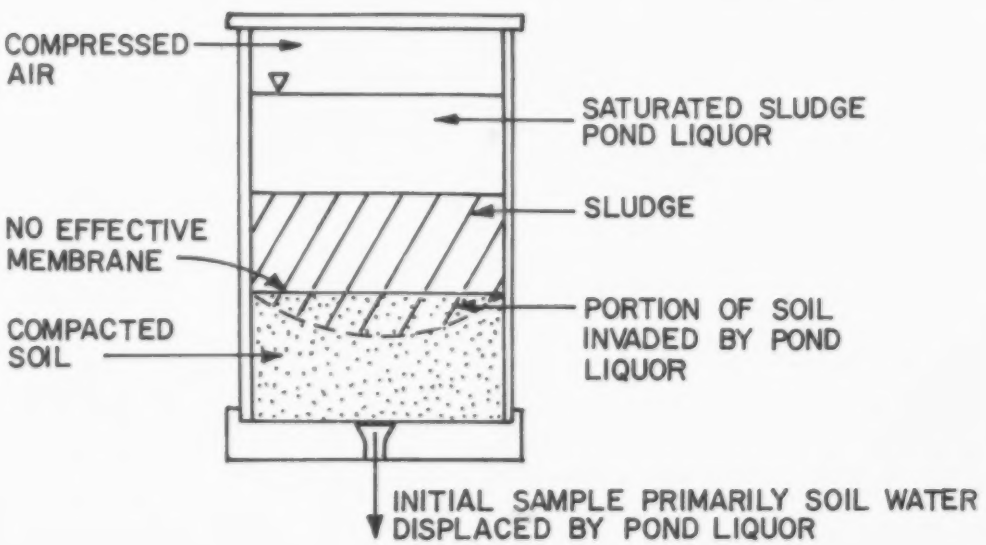
TACSS 020, and TACSS 025), as they had either passed all of the liquid sludge, failed before 12 months, or passed none (or an insufficient quantity for testing) of the liquid sludge after 12 months.

The first 32 oz of water collected from each test cell represents the first liquid that would be passing down into the saturated zone and mixing with the groundwater. This initial contribution arriving at the water table is a mixture of sludge liquor, materials from the liner and displaced interstitial water (pore water) from the soil. The extent of mixing of the concentrated solution from the sludge and soil water is directly related to the location of the soil mass that is invaded by the infiltrating sludge liquor. The leakage from a small rupture in a test membrane will seep directly through the soil under the leak (Figure 30a) and, by displacing only small amounts of soil pore water, will have a composition near that of the sludge liquor plus any contaminants from the membrane. For a test cell with no membrane or with a membrane passing liquid over a broad area, a shallower mass of soil is invaded initially, and the first liter of liquid reaching the test cell outlet is primarily displaced soil pore water (Figure 30b). Thus if the membrane passes water over the entire cross section of the test cell and sludge liquor moves through the entire soil/sludge interface, the initial permeate water sample will be very close to pore water in composition. The configuration of the leak by which sludge liquor passes through the membrane is probably the most decisive factor in determining the composition of the initial 32-oz water sample.

The concentration of a chemical constituent such as chloride, which is not effectively attenuated by soil, is an important indicator of how the sludge liquor is moving through the membrane. Tables 18 and 19 list the liners in order of the increasing chloride content of the initial permeate water samples. The spray-on liners AC40 and Sucoat both show low chloride


COMPRESSED AIR
SATURATED SLUDGE POND LIQUOR
SMALL BREAK IN MEMBRANE
SLUDGE
COMPACTED SOIL
PORTION OF SOIL INVADED BY POND LIQUOR.
INITIAL SAMPLE IS ONLY SLIGHTLY DILUTED POND LIQUOR

a. Small rupture in membrane.


COMPRESSED AIR
SATURATED SLUDGE POND LIQUOR
SLUDGE
NO EFFECTIVE MEMBRANE
COMPACTED SOIL
PORTION OF SOIL INVADED BY POND LIQUOR
INITIAL SAMPLE PRIMARILY SOIL WATER DISPLACED BY POND LIQUOR

b. Large rupture in membrane.

Figure 30. Pattern of leakage from membrane rupture.

TABLE 18. LINER MATERIALS ON SILTY SAND LISTED IN ORDER OF INCREASING CHLORIDE CONTENT OF THE INITIAL PERMEATE

Liner Material	Test Cells for Sludge A (Avg Cl, ppm)	Liner Material	Test Cells for Sludge B (Avg Cl, ppm)
AC40	63 (79)*	AC40	62
Sucoat	65	Sucoat	68 (91)
No liner	83	No liner	78
Total Liner	102	Aerospray 70	115
Aerospray 70	109	DCA-1295	135
Uniroyal	176	Uniroyal	182
DCA-1295	190	Dynatech	190
T16	212	Asphaltic concrete	196
Dynatech	214	Total Liner	202
Asphaltic concrete	460	T16	224
Sludge liquor	675	Sludge liquor	670

* ( ) Values at 24 months.

TABLE 19. LINER MATERIALS ON CLAYEY SILT LISTED IN ORDER OF INCREASING CHLORIDE CONTENT OF THE INITIAL PERMEATE

Liner Material	Test Cells for Sludge A (Avg Cl, ppm)	Liner Material	Test Cells for Sludge B (Avg Cl, ppm)
Portland cement plus lime	17	Portland cement plus lime	24
CST	38	CST	75
Lime	45	No liner	79*
No liner	95*	Portland cement	151
Portland cement	142 (167)†	Lime	152
TACSS 025	424	C400	462* (460)
M179	424	M179	502
TACSS 020	495	TACSS 025	512
Sludge liquor	675	Guartec UF	642
Guartec UF	1117	Sludge liquor	670
C400	-- (326)	TACSS 020	679

* Single sample.

† ( ) Values at 24 months.

levels in the initial liquid samples from Sludges A and B, suggesting that liquid was moving through the membrane along the entire cross section of the test cell. This hypothesis is borne out by observations made on the condition of the liners after the 12-month exposure. The AC40 liner developed a large leak in the center and had deteriorated so badly that it could not be removed intact from the test cell. The Sucoat liner had fractured, and insufficient material was available for postexposure testing. In the admix materials, the Portland cement plus lime and CST liners show very low chloride levels with Sludges A and B, again suggesting uniform permeation across the area of the test cell. Neither of these materials showed evidence of local small leakage when the cells used for 12-month exposure were examined. The conditions, observations, and chemical analyses of AC40, Sucoat, Portland cement, and C400 liners at 24 months had not changed significantly from the above.

As liquor continues to pass through these liner materials, the composition of the discharge from the test cells will approach the composition of the sludge liquor. In a typical sludge pond saturation, the decomposition products from the liner should be a minor problem compared with the high levels of pollutants in the ponded sludges. This study indicates that the characteristics of the leak are an important factor in the initial effect of the contained sludge liquor on the groundwater. However, if the liner fails, ultimately the full impact of sludge contamination will be felt.

PERMEABILITY

As mentioned previously, some leakage was caused by the silicone seals, which influenced the permeability values. Therefore, only zero permeability values and values of liners that were attacked by the chemical sludge(s) are reported. The permeability values for the liners that were chemically attacked may be influenced by the leaking seals.

SUMMARY OF LINER PERFORMANCE

Recorded data for physical tests (Tables 16 and 17) and chemical analysis (Tables 10 and 11) indicate that the following comments are valid and pertinent.

a. Total Liner. The density increased 26.2 percent following exposure, and the breaking strength decreased 72 percent. These figures indicate that the polymer was compacted and its strength was greatly reduced. The liner material was still soft and pliable, and it appeared to be in good condition.

b. T16. The density increased 14.5 percent, indicating some compaction of the polymer, but there was little or no change in the breaking strength. Some small, crusty formations were observed on the liner/sludge interface.

c. DCA-1295. The average density of this liner material decreased slightly (3.3 percent); however, both the elongation and the

breaking strength decreased significantly. Visual inspection revealed this liner was discolored and very thin. The liner was very easily torn while it was being removed from the test cell.

d. Dynatech. A 17.3-percent increase in density indicates some sludge infiltration into the sprayed material or compression of the polymer, although the other physical data remained essentially unchanged. Discoloration noted could be due to chemical attack during the testing.

e. Uniroyal. A 17.2-percent increase in density indicates some compression of the polymer and incorporation of sludge; the breaking strength decreased 40 percent. Liner discoloration noted could indicate susceptibility to chemical attack.

f. Aerospray 70. A 33.3-percent increase in density indicates considerable sludge incorporation and polymer compaction. The breaking strength decreased 57 percent, although one of these test cells did not pass any leachate. Discoloration and thin spots were observed throughout the liner. Decomposition was noted on the membrane/soil interface.

g. AC40. The physical tests performed on this liner material made it difficult to detect any chemical degradation of the liner. The average viscosity appeared to be very high at the end of the first 12 months, but this figure had returned to nearly the original value by the end of 24 months. Leakage from these test cells was passing through the liner material itself. Chemical data indicate that leakage from the test cell contained four to six times the concentrations of chromium, selenium, boron, and sulfate at 24 months than at 12 months.

h. Asphaltic concrete. These physical tests were identical to those for AC40 and essentially the same comments are appropriate.

i. Portland cement. The density of this liner material remained essentially unchanged, but the UC strength increased 175 percent. Chemical data indicate that leakage from the test cell contained approximately seven times higher concentrations of sulfite and sulfate at 24 months. The liner was soft and friable in isolated areas.

j. Lime. The 1.1-percent increase in density of this liner material may indicate slight sludge infiltration or compaction of the liner, but it is more likely that this change represents a normal variation in density across the specimen. The UC values of this liner increased 464 percent. Chemical data indicate the leakage from the test cell contained 5 to 20 times higher concentrations of chromium and boron after 12 months, whereas the concentrations of magnesium, sulfate, nitrite, and nitrate decreased as much as 150 times.

k. Sucoat. This liner was supplied preformed by the manufacturer and apparently suffered no chemical decomposition. One test cell

ruptured under pressure and was discontinued. Chemical data indicate that leakage from the test cell contained 2 times the concentrations of magnesium and sulfate, 5 times the concentration of boron, and 100 times the concentrations of nitrite and nitrate at 24 months than at 12 months. The breaking strength was reduced 16 percent at the end of 24 months.

l. TACSS 020 and TACSS 025. Neither of these two liner materials evidenced any change in density other than what could be normally expected during a typical construction procedure. Sludge penetrated the surface of the liner more than 3/8 in. on each liner type.

m. Portland cement plus lime. No significant change in density occurred during the 24-month test (+0.3 percent). Chemical data indicate that the leakage through the liner contained approximately 40 times greater concentrations of chromium at 12 months; whereas the concentration of magnesium decreased approximately 0.01 times, and the concentrations of nitrite, nitrate, and sulfate decreased 0.01 to 0.001 times. The UC strength increased 187 percent.

n. C400. No significant change in density occurred during the 24-month test (+0.3 percent). The UC strength increased 106 percent. The chemistry of the leachate through the test cell indicates that approximately 3 times the concentrations of arsenic and boron and 20 times the concentrations of chromium and selenium were detected at 24 months than at 12 months. Indications were that the copper and lead concentrations also increased.

o. CST. No significant change in density occurred during the 24-month test (+0.3 percent). The UC strength increased 63 percent. The chemical concentration of the leachate at 12 months increased approximately 20 to 100 times for sulfate and nickel, respectively; whereas the concentration of leachate for nitrite and nitrate decreased up to 0.001 times, and for magnesium reduced by a factor of approximately 0.01.

No definite trends were established from these tests that would permit the projection of liner life with any degree of accuracy.

SECTION 8

ECONOMIC ASSESSMENTS

Material and construction costs in this section are based on a typical 15-acre lagoon that will accommodate 30 ft of water. The cost of the land and the initial preparation (grubbing, clearing, digging, etc.) are not considered in this discussion as they are affected by location, density of population and vegetation, and soil formation. The assumption here is that the 15-acre sump (30 ft deep) is ready and available to be lined with the liners discussed previously. Tables 20 and 21 give the material cost of each liner at point of purchase.

ADMIX LINERS

For all of the admix materials except the asphaltic concrete, the surface of the prepared site is scarified to a depth of 6 in. using a rotary mixer (Figure 1). Material costs were obtained from suppliers, and construction costs were derived from the Mississippi State Highway Department, contractors, news items, literature, and past experience.

Lime

The area is scarified or pulvimixed, and the desired percentage of lime is added as a slurry mix from a distributor truck. The soil/lime mixture is again pulvimixed, and water is added to 5 percent above optimum water content. Compaction is accomplished with a heavy pneumatic or vibrating roller or a combination of sheepsfoot and light pneumatic roller to achieve maximum density. In some heavy clays, it may be necessary only to compact the mixture lightly and allow the mixture to mellow for 2 to 5 days. The mixture is repulvimixed, watered, and rerolled for compaction. The lime should only be added to an area that can be mixed in one day and used only when the soil temperature is 40°F or higher to ensure a proper chemical reaction producing maximum strength. Unnecessary traffic should be kept off the finished liner for 3 to 7 days while the soil/lime mixture cures (15). Equipment needed for this job consists of a pulvimixer, lime distributor truck, water truck, rubber-tired roller, and a centrifugal pump with hose. A work crew consisting of approximately 10 laborers, 4 equipment operators, and a foreman will probably require from 6 to 15 days to complete the job. Cost estimates in the southeastern states are \$80 to \$100/ton for lime and \$0.70 to \$1.10/yd^2 for mixing and finishing the area. The cost per square yard for the lime and the installation will range from \$2.50 to \$3.35 based on information received from the Mississippi State Highway Department and area construction contractors.

TABLE 20. COST OF ADMIX MATERIALS

Liner Material	ID No.	Application Rate (%)	Cost per Ton	Cost per yd^2	Total Cost/ 15 Acres
Portland cement	10	10	$ 90.00	$2.00	$ 150,000
Lime	12	10	90.00	2.00	150,000
Portland cement plus lime	15	4/6	90.00	2.00	150,000
Asphaltic concrete	09	11	25.00*	7.90	600,000
TACSS 020	14	6	4158.73	56.00	4,100,000
TACSS 025	16	6	4285.71	58.00	4,300,000
C400	17	15	?†	?	?
CST	18	15	?	?	?

* In place.
† ? = Data not provided.

TABLE 21. COST OF SPRAY-ON AND MEMBRANE MATERIALS

Liner Material	ID No.	Application Rate	Cost Quote	Cost per yd^2	Total Cost/ 15 Acres
Total Liner	01	100%	$0.25/$ft^2$	$2.25	$ 164,000
T16	02	100%	1450/2500 ft^2	5.20	400,000
DCA-1295	03	0.75 gal/yd^2	3.07/gal	2.30	200,000
Dynatech	04	0.75 gal/yd^2	9.00/gal	6.75	500,000
Uniroyal	05	0.75 gal/yd^2	4.84/gal	3.60	300,000
Aerospray 70	06	0.75 gal/yd^2	4.54/gal	3.40	300,000
AC40	07	0.75 gal/yd^2	0.60/gal	0.45	33,000
Sucoat	13	3/8 in.	2.00/ft^2 in-place	18.00	1,350,000

Portland Cement

The area is pulvimixed to a depth of 6 in., and loose cement is spread from a distributor truck at a desired rate of application (10 percent). The soil/cement is watered, and mixing is continued. When the soil/cement is thoroughly mixed (soil color is uniform), compaction is begun immediately (in less than 1 hour) to prevent hydration before compaction is completed. Pneumatic-tired and sheepsfoot rollers are used for initial compaction, and steel-wheeled rollers are used to finish the surface. The soil temperature should be above 40°F for the rapid chemical reaction necessary to achieve maximum strength. Unnecessary traffic should be barred from the area as the cements cure for approximately 7 days (16). The equipment, manpower, and time needed to install the cement liner are essentially the same as those needed for the lime liner, except that a steel-wheel roller is required to compact the area to a smooth finish. The cost per square yard is generally about $0.05 higher than for mixing lime based on information received from the Mississippi State Highway Department and area construction contractors.

Portland Cement Plus Lime

When cement plus lime is used, the temperature that controls each material (described above) should be observed. The area is scarified or pulvimixed, and the desired percentage of lime is added as a slurry mix from a distributor. The additive is throughly mixed and watered with the soil and rolled lightly. The mixture is allowed to set from 1 to 2 days to mellow. The lime-conditioned soil is scarified, and the cement is added. The additives are again thoroughly pulvimixed. Water is added during mixing as needed. Pneumatic-tired and/or sheepsfoot rollers are used for maximum compaction, and the final rolling is done with a steel-wheel roller. Essentially the same manpower and equipment will be required as described for cement above. The cost per square yard for the materials, mixing, and finishing is estimated to be in the range of $2.50 to $3.35.

Asphaltic Concrete

The asphaltic concrete using 1/2-in. maximum-sized aggregate with 11 percent asphalt content costs $7.90/yd^2 in place (Table 20). The high percent of asphalt will produce near-zero voids, making the liner nearly impervious. However, special care will have to be exercised in compacting (rolling) the asphalt to prevent rutting. A steel-wheel roller is recommended for compaction.

Other Admix Liners

The Takenaka Komoten Company of Japan did not give a quotation on the cost of the C400 or the CST liner material. However, they did provide the cost for the TACSS 020 and TACSS 025 materials, as shown in Table 20. Information on construction cost, method of application, and techniques in placing these materials were not provided.

PREFABRICATED MEMBRANE LINERS

The two membranes tested were essentially the same thickness and weight. To line a 15-acre lagoon would require the same total area and identical size and length of bonded joints; therefore the cost of placement would be assumed to be the same. The size of a section of membrane would depend on the configuration of the lagoon. The larger the section of membrane that can be handled conveniently and properly, the fewer bonded joints will be required, which is desirable. Assuming the 15-acre lagoon is 5 by 3 acres (1050 by 650 ft), a convenient liner size to purchase and handle is 650 by 105 ft, which weighs 8768 lb. The membrane sections are accordion-folded from each side (length) to the center, and the section is again accordion-folded from the bottom to the top of the bundle. Eleven sections will be required to line the lagoon completely and anchor the edges. A total of 6500 linear ft of bonded joints (6 in. wide) will be required to connect all sections. A section can be placed from the back of a truck by releasing the accordion folds as the truck travels along the longitudinal center line of the area to be covered. Thirty men (one every 20 ft) can unfold the section to cover half the width of the section in one direction, and then the other half in the opposite direction. A large area can be covered, as the membrane can be flapped or pumped by the men so that it seemingly floats on a cushion of air. Succeeding sections are similarly placed, overlapping the previously placed section by 6 in. for bonding sections together. Anchor ditches around the periphery of the lagoon are required to anchor the edges of the membrane. Table 22 gives the time, equipment, manpower, and cost to accomplish the job. The estimated cost, at rates of $7/hr for laborers and $12/hr for operators, is $38,154 per job. When a factor of 2.35 is used for overhead, the cost becomes approximately $90,000--$0.14/ft^2, or $1.24/yd^2 for installation. The total cost of material ($2.25/yd^2 for the Total Liner and $5.20/yd^2 for the T16 membrane as shown in Table 21) plus the installation cost ($1.24/yd^2) gives a total in-place cost of $3.51/yd^2 for the Total Liner and $6.46/yd^2 for the T16 membrane.

SPRAY-ON LINERS

Essentially the same equipment is required to apply all of the spray-on liners. Most contractors have more experience in using bitumen, and their equipment is geared to the use of this material. Therefore, the cost of applying the bitumen materials is less than for other similar applications.

AC40

For application, an asphalt distributor will be required, and the material will have to be heated above 400°F for the material to flow for spraying. On flat terrain, this material can be applied at a total cost of $0.90/yd^2. On sloping banks of a lagoon, hand spraying and labor will increase the cost to approximately $1.30/yd^2.

DCA-1295

An asphalt distributor can be used to apply the DCA-1295 material. The

TABLE 22. EQUIPMENT, TIME, COST, AND MANPOWER TO PLACE PREFABRICATED MEMBRANE LINERS

Operation	No. of Personnel	Equipment Required	Time Required (hr)	Time Required Man-Hours	Total Estimated Cost*
Constructing anchor ditch (1 ft deep by 3400 ft long)	1	Motor grader	6.0	6.0	$ 9,100
Compacting	1	Rubber-tired roller	24.0	24.0	5,550
Removing surface water	2†	Centrifugal pump & hose	As needed	--	1,400
Removing wooden crates from liner package	2‡	Quick way, truck-mounted crane	2.0	2.0	7,652
Transporting liner along center line of placement area	1	2-1/2-ton truck	2.5	77.5	4,372
Unfolding, stretching, and placing membrane in anchor ditch with enough soil to anchor	30	---	12.0	360.0	10,080
Bonding sections together (6 in. by 6500 ft)	2 crews of 5† each	---	0.5	5.0	
Backfilling anchor ditch	1	Motor grader	6.0	6.0	§
Total	34 (30 placing crew, 4 equipment operators)	1 motor grader 1 rubber-tired roller 1 truck-mounted crane 1 2-1/2-ton truck 1 centrifugal pump	53.0	478.5	$38,154

* Includes laborers, operators, equipment, fuel, and mobilization.
† Included in the 30 laborers needed for unfolding and stretching the liners.
‡ One of 30 laborers.
§ Included in cost for construction of anchor ditches.

orifices on the spray bar will have to be replaced for the DCA-1295. The material is required to be recirculated at a rate of 100 to 120 gal/min in the distributor to prevent settling. The material is not a lubricant for the pumps (as asphalt is), and grease fittings will be required to lubricate the pump. Also, the DCA-1295 will set up in the pump on short downtime (15 min or more), and the pump will have to be cleaned (17). It is estimated that the total cost of materials and installation on a 15-acre lagoon will be \$3.50 to \$3.80/yd^2.

Aerospray 70

The Aerospray is similar to the DCA-1295, and it is applied with the same equipment and labor. Because of the higher material cost, the total cost per square yard will be approximately \$4.75 to \$5.00.

Dynatech and Uniroyal

Both materials are a natural latex and are applied as a liner similarly to the DCA-1295. Each is applied at the same rate (0.75 gal/yd^2) and requires the same or similar handling and manpower. The estimated total cost of the installed Uniroyal and Dynatech is \$4.90 to \$5.20 and \$8.00 to \$8.25/yd^2, respectively.

Sucoat

Sucoat is a molten sulfur product that is placed at a high temperature (300° to 400°F) and forms a strong solid upon curing. The manufacturer's estimated cost of the material in place is \$18/yd^2.

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APPENDIX A

MANUFACTURER/ADDRESS FOR THE SELECTED LINER MATERIALS

Material	Manufacturer/Address
Type I Portland Cement	Local Distributor
Hydrated Lime	Local Distributor
Portland Cement with Lime	Local Distributor
M179	Dowel Division of Dow Chemical
Guartec UF	General Mills
Asphaltic Concrete	Local Contractor
TACSS 020	Takenaka Komuten Co. (Japan)
TACSS 025	Takenaka Komuten Co. (Japan)
C400	Takenaka Komuten Co. (Japan)
CST	Takenaka Komuten Co. (Japan)
DCA-1295	Union Carbide
Dynatech Formulation 267	Dynatech R&D Co.
Uniroyal	Uniroyal Inc.
Aerospray 70	American Cyanamid
AC40	Globe Asphalt
Sucoat	Chevron Chemical Co.
Total Liner	Goodyear Tire & Rubber Co.
T16	Reeves Brothers, Inc.